COMBUSTION

DEVOTED TO THE ADVANCEMENT OF STEAM PLANT DESIGN AND OPERATION

September 1957

Final check-out of the fully automatic controls on Unit 5, Seward Station, Pennsylvania Electric Co. See pp. 44-48 for a photo sequence on placing these controls into service.

Analog Computer In Nuclear Plant Design

Improving Coal Sample Accuracy

Servomechanisms In Combustion

COMBUSTION

DEVOTED TO THE ADVANCEMENT OF STEAM PLANT DESIGN AND OPERATION

Vol. 29 **No. 3**

September 1957

Feature Articles

Editorials

Departments

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BPA

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Ljungstrom maintenance is fast and easy because it, too, is a "designed-in" function of the preheater. Necessary work has been foreseen by such money-saving features as:
• Self-cleaning action that loosens deposits by expansion and contraction—coupled with high-velocity soot blowers for daily in-operation purging.
• Cold-end heating elements are factory packed—can be easily replaced, or reversed when one edge starts to thin... which is vital for cold end service and essentially doubles surface life.
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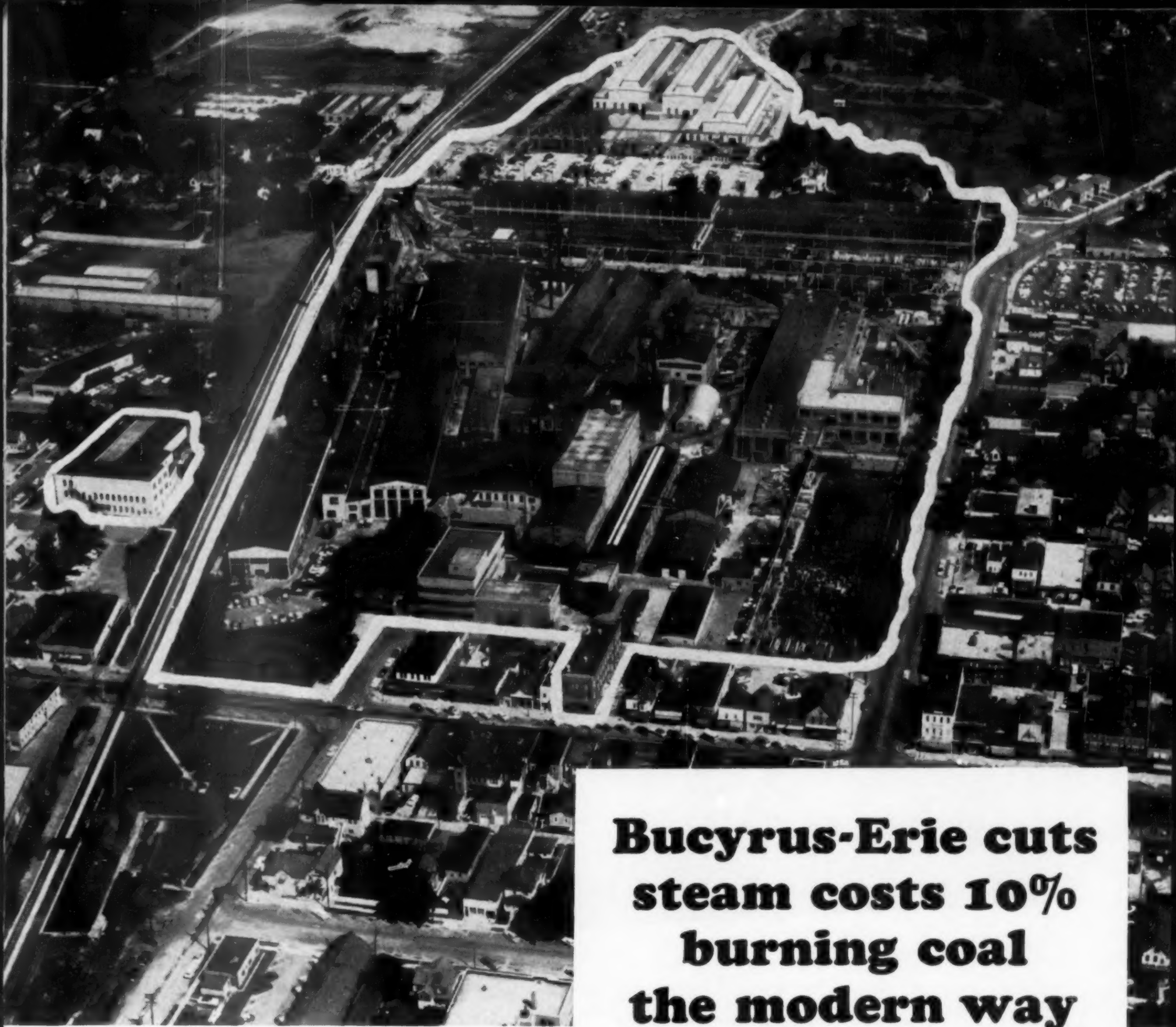

Bucyrus-Erie cuts steam costs 10% burning coal the modern way

Consult an engineering firm

Designing and building hundreds of heating and power installations a year, qualified engineering firms can bring you the latest knowledge of fuel costs and equipment. If you are planning the construction of new heating or power facilities—or the remodeling of an existing installation—one of these concerns will work closely with your own engineering department to effect substantial savings not only in efficiency but in fuel economy over the years.

facts you should know about coal

In most industrial areas, bituminous coal is the lowest-cost fuel available. • Up-to-date coal burning equipment can give you 10% to 40% more steam per dollar. • Automatic coal and ash handling systems can cut your labor cost to a minimum. Coal is the safest fuel to store and use. • No smoke or dust problems when coal is burned with modern equipment • Between America's vast coal reserves and mechanized coal production methods, you can count on coal being plentiful and its price remaining stable.

Bucyrus-Erie Company, South Milwaukee, Wis., had a steam generation problem. Not only was original equipment deteriorating but capacity proved inadequate for expanding plant facilities. Working with consultants Gates, Weiss and Kramer, of Milwaukee, the company decided to modernize its power system.

Today the power plant at Bucyrus-Erie is almost completely automatic and utilizes the newest coal-burning and handling equipment. In addition to increasing steam generating capacity 85%, this modernization program has lowered annual steam production costs 10% and labor costs 35%. Burning coal the modern way has increased steam quality, improving production processes and heating throughout the plant.

For additional case histories on burning coal the modern way or for technical advisory service, write to the address below.

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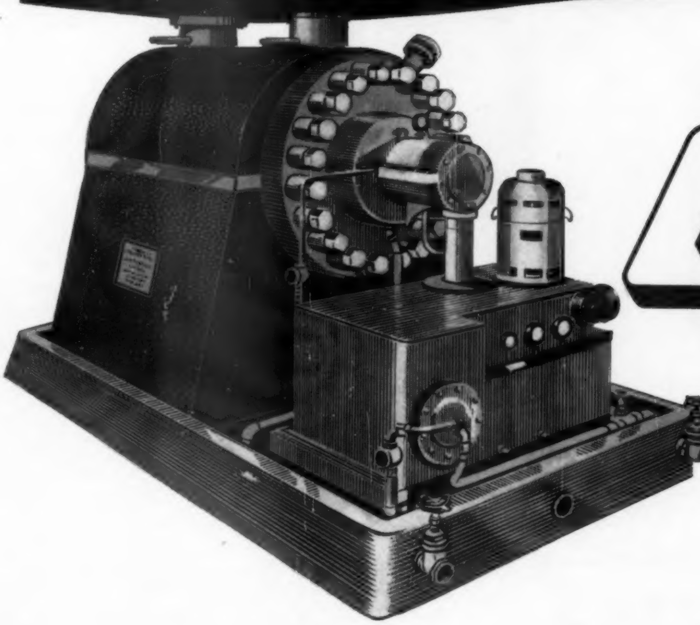
PACIFIC Boiler Feed Pumps



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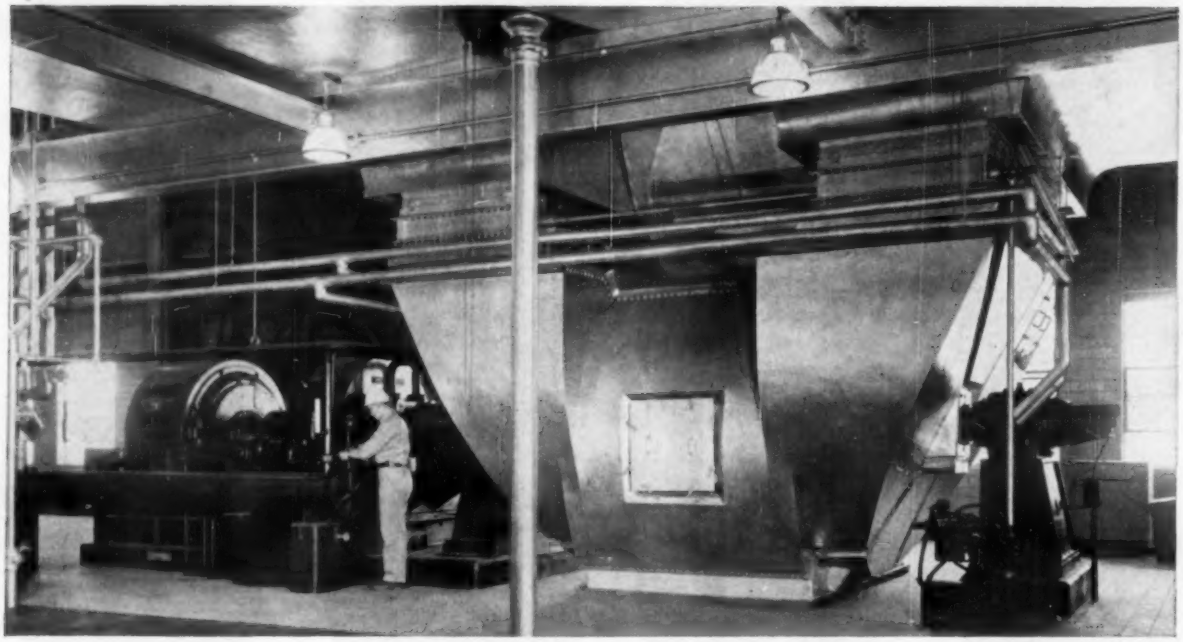
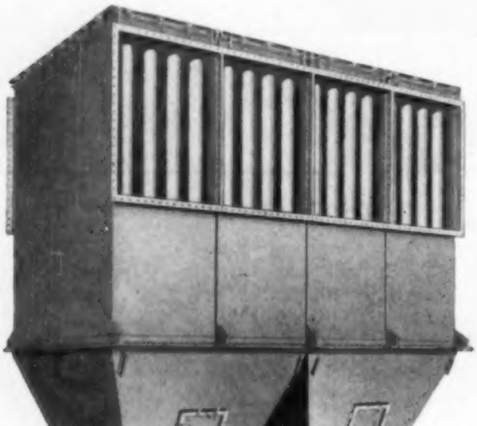
American Blower Air-Handling Equipment

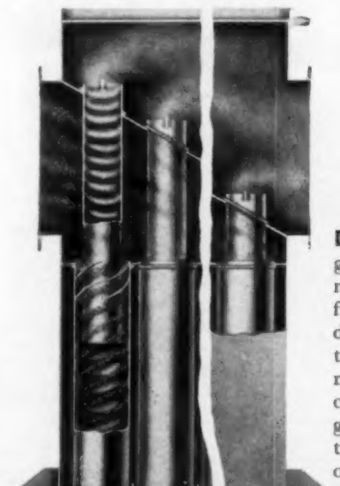
Proved efficiency



American Blower Induced-Draft Fans offer high static efficiency at low rpm. Like all American Blower mechanical-draft equipment, they are accurately formed and welded; fan rotors carefully balanced; all parts are minutely inspected for dimensional accuracy. They require a minimum space and minimum maintenance.



Series 342 Precipitator is easy to install and very effective in controlling fly ash. The over-all performance of each tube is comparable to the high efficiency of a small-diameter cyclone.



Dust-laden air or gas enters inlet plenum; gravity and centrifugal action force dust downward, adjacent to tube wall; dust is skimmed into gas-tight receptacle; cleaned air or gas moves upward through outlet tubes to outlet plenum.

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American Blower Mechanical Draft Fans

To meet the peak efficiency demanded of mechanical-draft equipment today, you'll be better off if you select spacesaving and efficient American Blower Mechanical Draft Fans.

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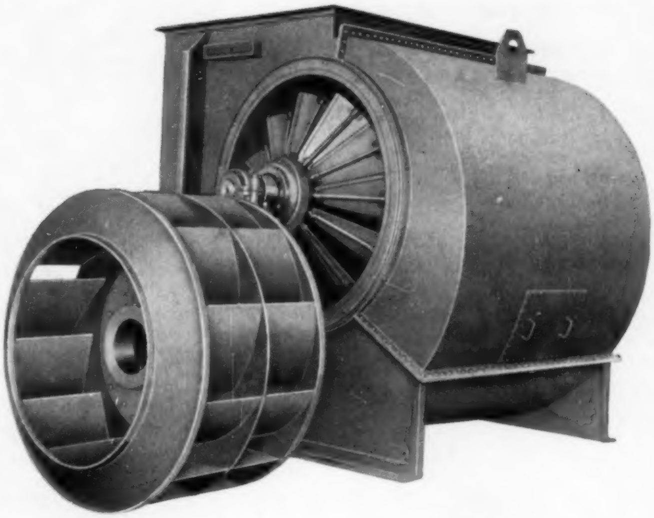
If you are investigating mechanical-draft equipment—for new or existing installations—you'll do well to check on American Blower's line of Mechanical Draft Fans with guaranteed performance ratings. We welcome the opportunity of quoting on your requirements.



Forced Draft Fans for quiet indoor or outdoor installations. Heavy, reinforced housings and wheel-shaft assembly mean longer life, while special streamline inlets give utmost efficiency.

American Blower Precipitators

For maximum collection efficiency, choose the *best*—a dependable American Blower Precipitator!

Your fly ash problems can be met by installing a Series 342 Fly Ash Precipitator which offers good efficiency over the normal operating range, while it gives reliable, trouble-free performance.

American Blower's line of Fly Ash Precipitators and Dust Collectors has gained wide acceptance in leading public utilities and industrial plants.

For complete information on American Blower Dust Collectors and Precipitators as well as other air handling products, call our nearest branch, or write direct. American Blower Division of American-Standard, Detroit 32, Michigan. In Canada: Canadian Sirocco products, Windsor, Ont.

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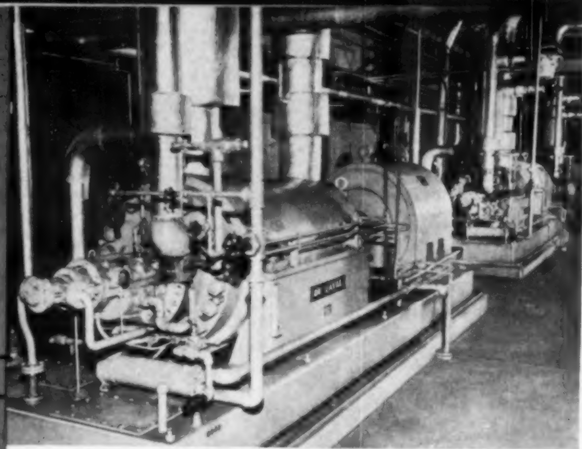

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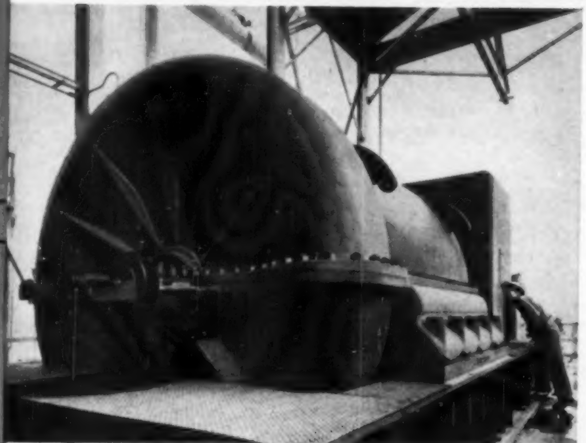

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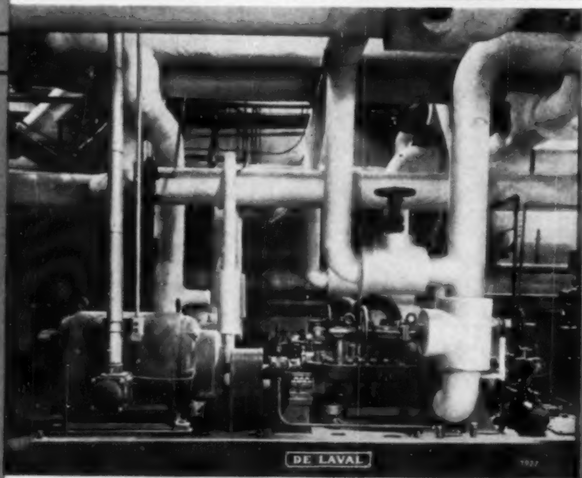

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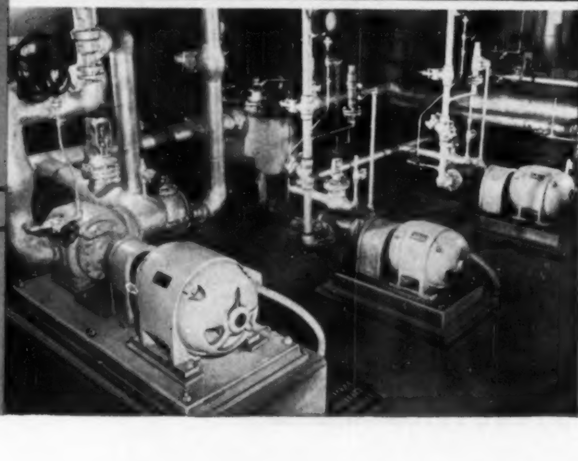

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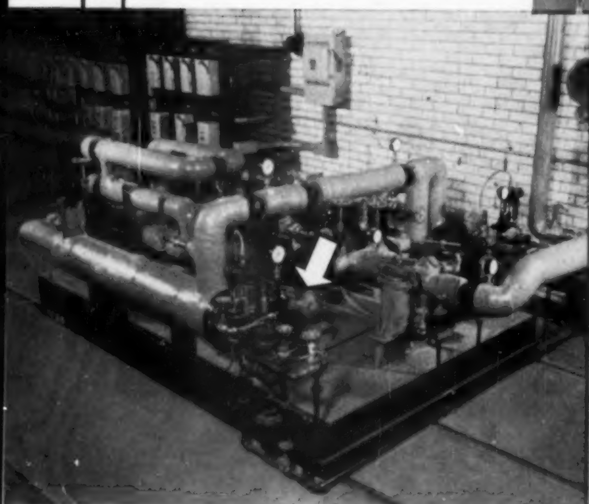

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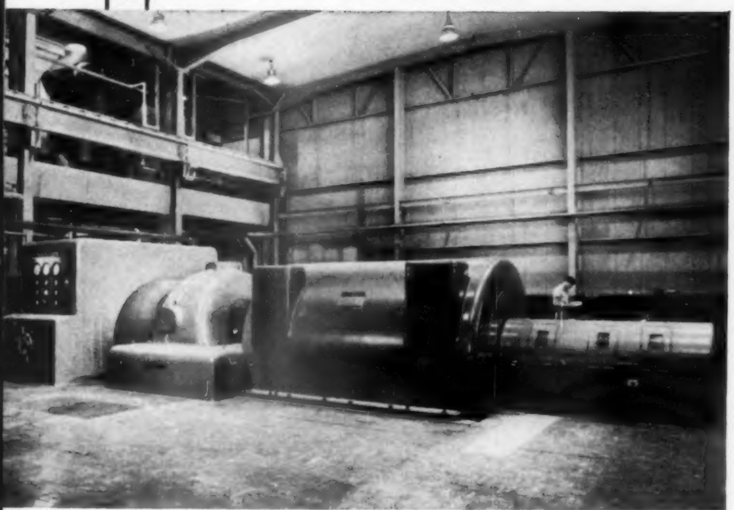
6



Machines
that *stay* in service
year in and year out
are the most economical.
Since 1901,
De Laval has supplied
quality-designed pumps,
compressors, and other
vital equipment for the
power industry.
Each unit is designed
for dependability and
built by master craftsmen.
As a result, the De Laval
name plate is your
assurance of reliability.
Literature is available
on all equipment
shown on these pages.

DE LAVAL Steam Turbine Company

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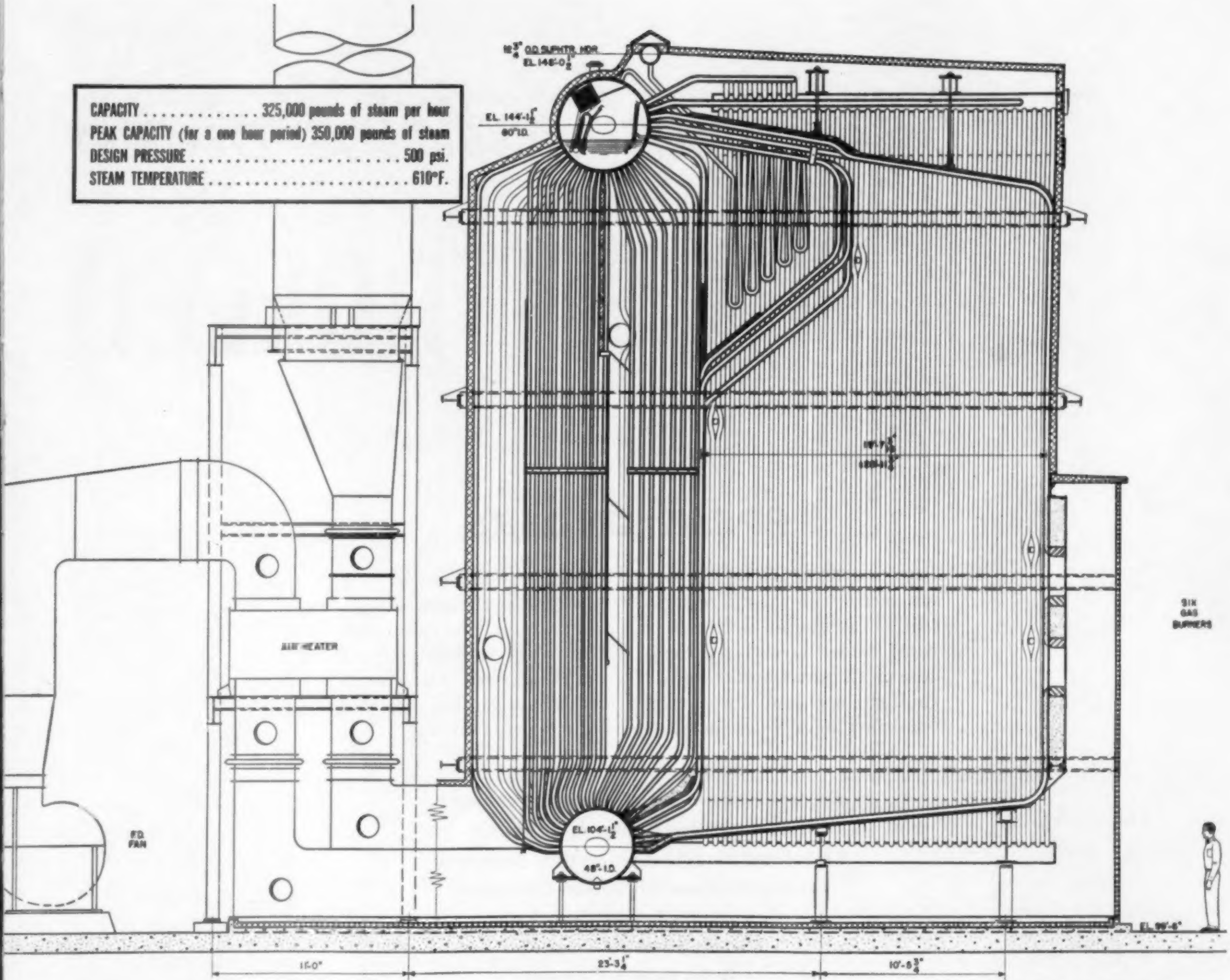
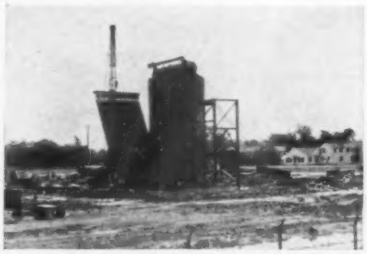
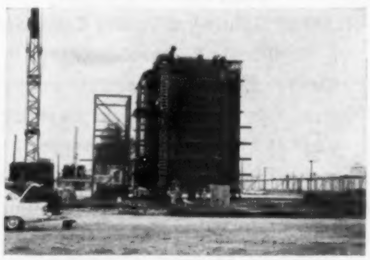
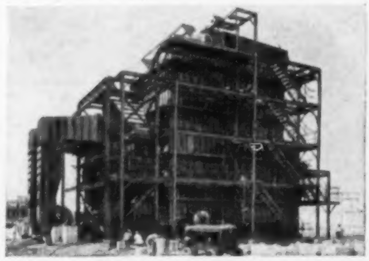




HEADER WITH PRE-ASSEMBLED TUBING is quickly and efficiently raised into position by crane used for building construction. Beyond savings in time, this technique makes top quality of completed unit easier to achieve.



FINAL STAGES OF ERECTION include a careful inspection. Republic ELECTRUNITE Boiler Tubes provide maximum reliability throughout every length. There are no hidden thin spots to threaten service life or cause uneven heat transfer.



JACKET INSTALLED, Riley Steam Generator is virtually complete. Republic offers a handy guide outlining proper protection of boiler installations. Send coupon for wall chart entitled "Care and Maintenance of Boiler Tubing", today.

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their FIRST ORDERS for

CIRCULATION BOILERS

Five years ago, the Virginia Electric & Power Company initiated a major new trend when it placed in service a C-E Controlled Circulation Boiler.

The rapidity with which this trend has developed is evidenced by the fact that orders for C-E Controlled Circulation Boilers now total *111* units having an aggregate capacity of more than

19,300,000 kw

Recently, the following utility companies have placed their first orders:

	Station	No. of Units	Kw Capacity per unit
Central Illinois Public Service Co.	Meredosia	1	200,000
Consolidated Edison Co. of New York	Astoria	1	340,000
Florida Power & Light Co.	Port Everglades	2	240,000
Pennsylvania Power & Light Co.	(new station)	1	330,000

The *repeat order* list opposite reveals the nationwide acceptance of the C-E Controlled Circulation Boiler. The rapidly growing preference for this boiler is the result of its outstanding performance record, particularly with respect to high availability, and the widespread recognition of its special suitability for high pressures. This preference is particularly notable in the 2400-lb pressure range where the C-E Controlled Circulation Boiler leads the field by a wide margin with 36 units installed or on order for a total capacity of 6,600,000 kw.

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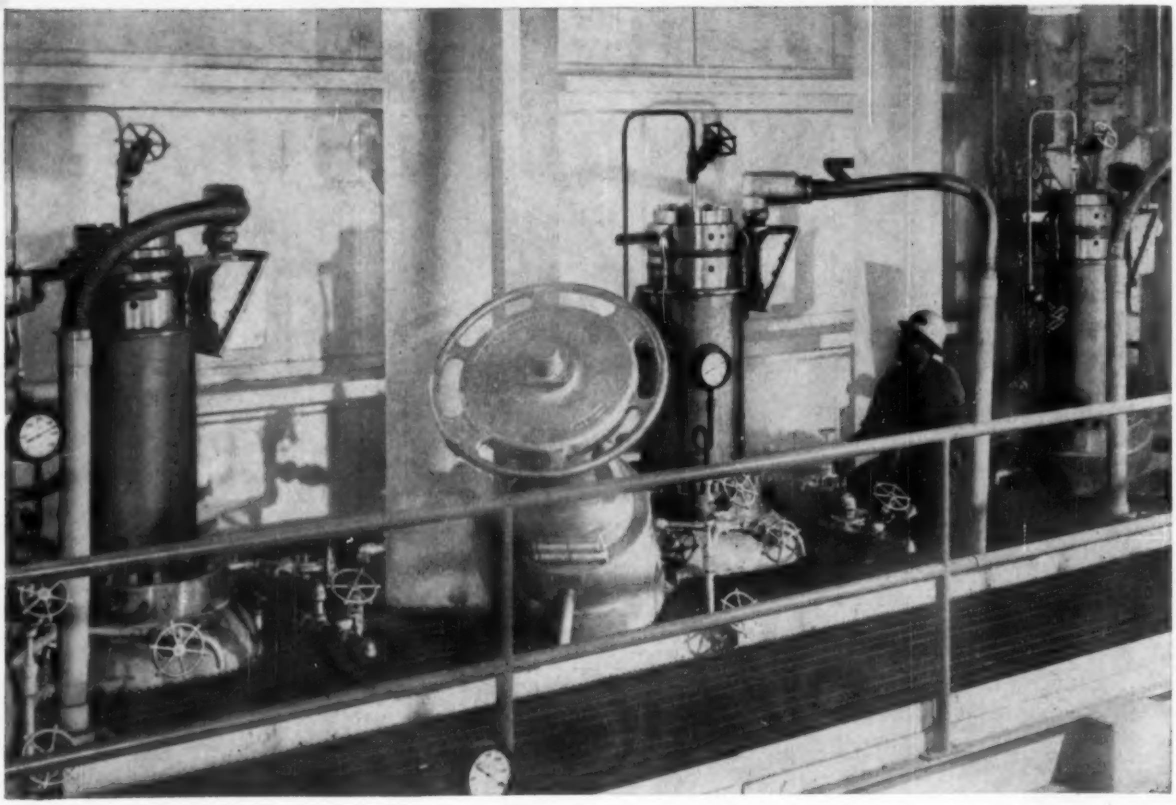
C-111

ALL TYPES OF STEAM GENERATING, FUEL BURNING AND RELATED EQUIPMENT; NUCLEAR REACTORS; PAPER MILL EQUIPMENT; PULVERIZERS; FLASH DRYING SYSTEMS; PRESSURE VESSELS; SOIL PIPE



Bailey Meters and Controls for Combustion, Feed Water, Steam Temperature and Condensate at Moores Park Station, City of Lansing, Michigan.

How Bailey makes steam operating duties a pleasure—

Fingertip Controls, convenient indicators and trend recorders make steam control room operating duties a pleasure. You get this bonus for your operators when you specify Bailey Meters and Controls.

Bailey is the choice of virtually all the most efficient plants on the Federal Power Commission's heat rate report. Here's why:

1. A Complete Line of Equipment

You can be sure a Bailey Engineer will offer the right combination of equipment to fit your needs.

Bailey manufactures a complete line of standard, compatible pneumatic and electric metering and control equipment that has proved itself. Thousands of successful installations involving problems in measurement, combustion, and automatic control are your assurance of the best possible system.

2. Experience

Bailey Engineers have been making steam plants work more efficiently for more than forty years. Veteran engineer and young engineer alike, the men who represent Bailey, are storehouses of knowledge on measurement and control. They are up-to-the-minute on the latest developments that can be applied to your problem.

3. Sales and Service Convenient to You

There's a Bailey District Office or Resident Engineer close to you. Check your phone book for expert engineering counsel on your steam plant control problems.

A133-1

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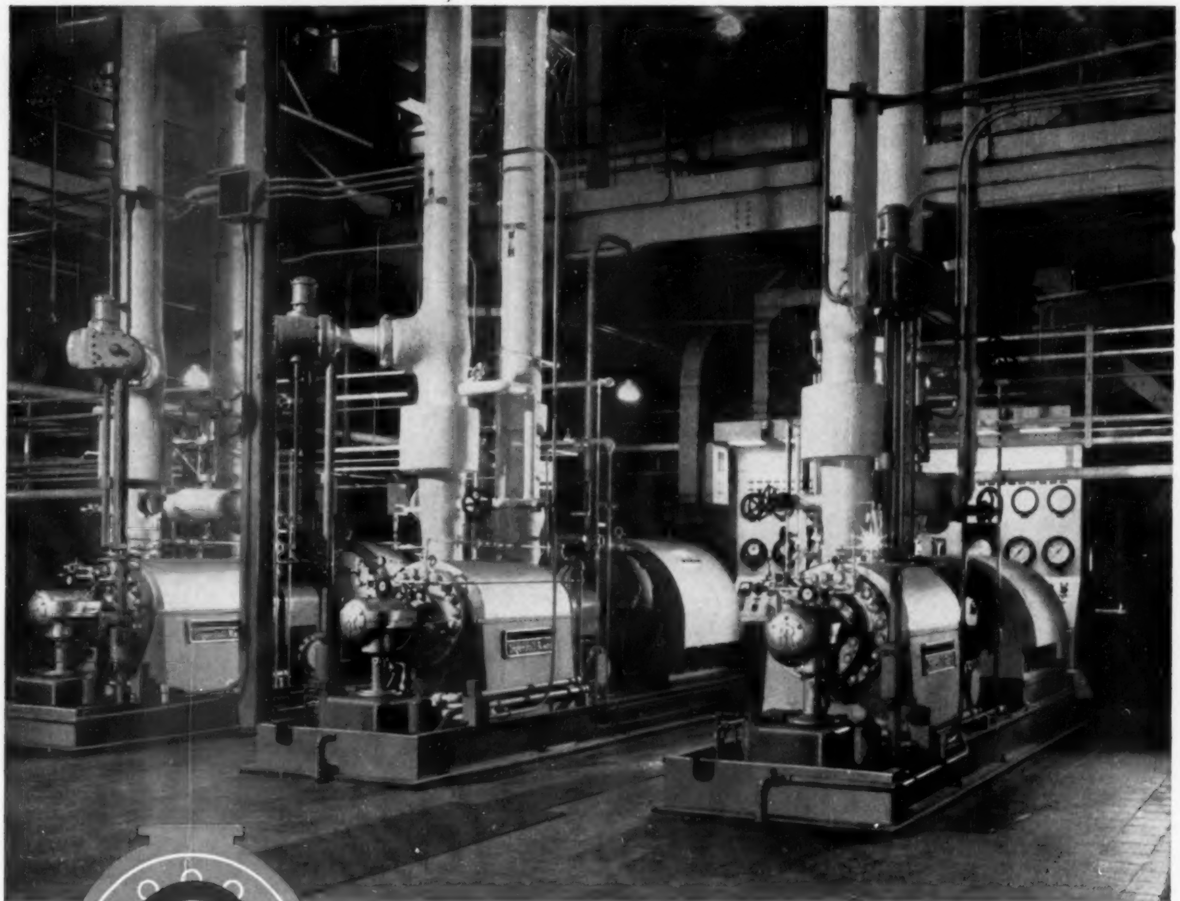

6 I-R BOILER FEED PUMPS

now serving ALL THREE Generating Units at

MUSTANG STATION

of Oklahoma Gas & Electric Co.

At its Mustang Station, Oklahoma Gas & Electric Company looks to Ingersoll-Rand boiler-feed pumps for the dependable, efficient supply of feedwater to all three of the station's generating units.

Pictured above are three of the four 1100-gpm, 1250-psi discharge units which serve 50-MW Units No. 1 and No 2. The new 100-MW Unit No. 3, put into operation in 1955, is served by another pair of Ingersoll-Rand boiler-feed pumps, each designed for 1770-gpm, 1900-psi discharge. While each generating unit is served by two pumps, each pump is capable of handling full unit load.

All six boiler-feed pumps are of proven Ingersoll-Rand heavy-duty, double-case design, featuring "unit-type" rotor construction to facilitate inspection and servicing.

Ingersoll-Rand boiler-feed pumps are the Power Industry's first choice where efficient performance and maximum dependability are prime considerations. They are available for all capacities and pressures, for any central station or industrial application. Your local I-R engineer can give you full details.

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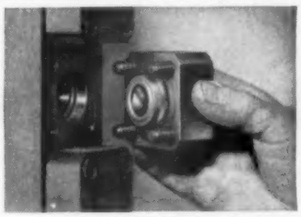
gives you . . . two-color readings
. . . low maintenance
. . . increased availability

You get a *triple advantage* with the Yarway COLOR-PORT boiler water level gage for pressures to 3000 psi.

Two-color readings are brilliant and clear. Water shows green; steam shows red. A full gage is all green and an empty gage all red.

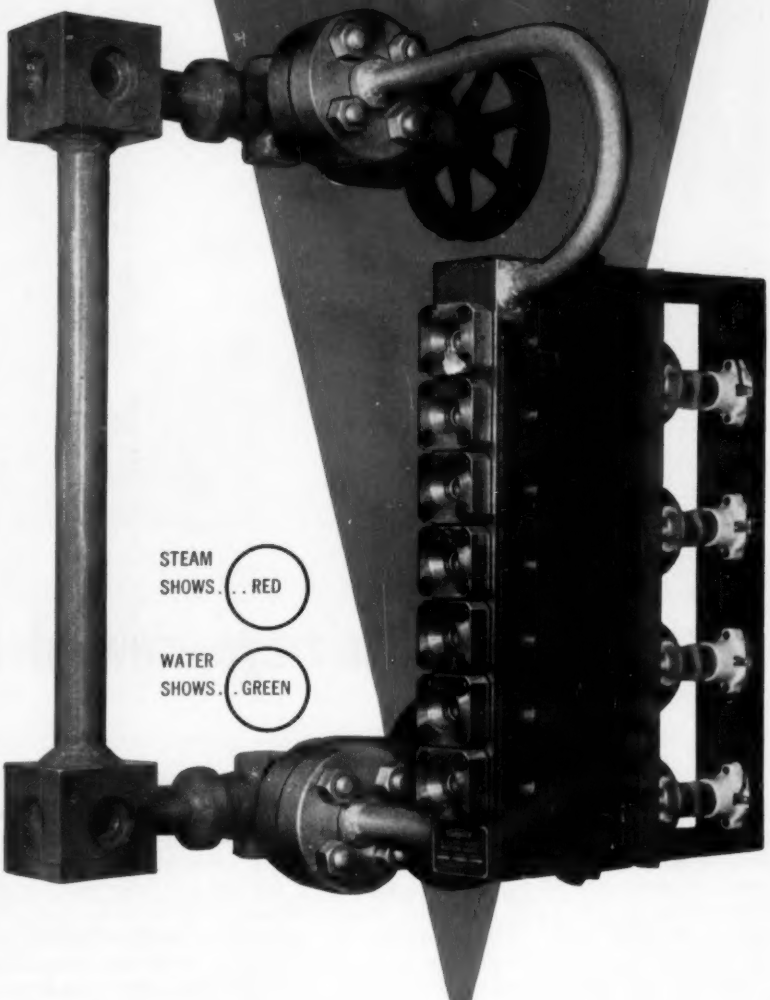
Low maintenance with individual cover-glass assemblies, each held solidly in place by four socket head cap screws. "Floating assembly" design applies safe, predetermined loads on glass ports, reducing thermal shocks, permitting faster warm-up.

Increased availability means longer service life. Cover glass assemblies can be *serviced in place*, easily and quickly.



Yarway Bulletin WG-1814 describes the Color-Port Gage. Write for it.

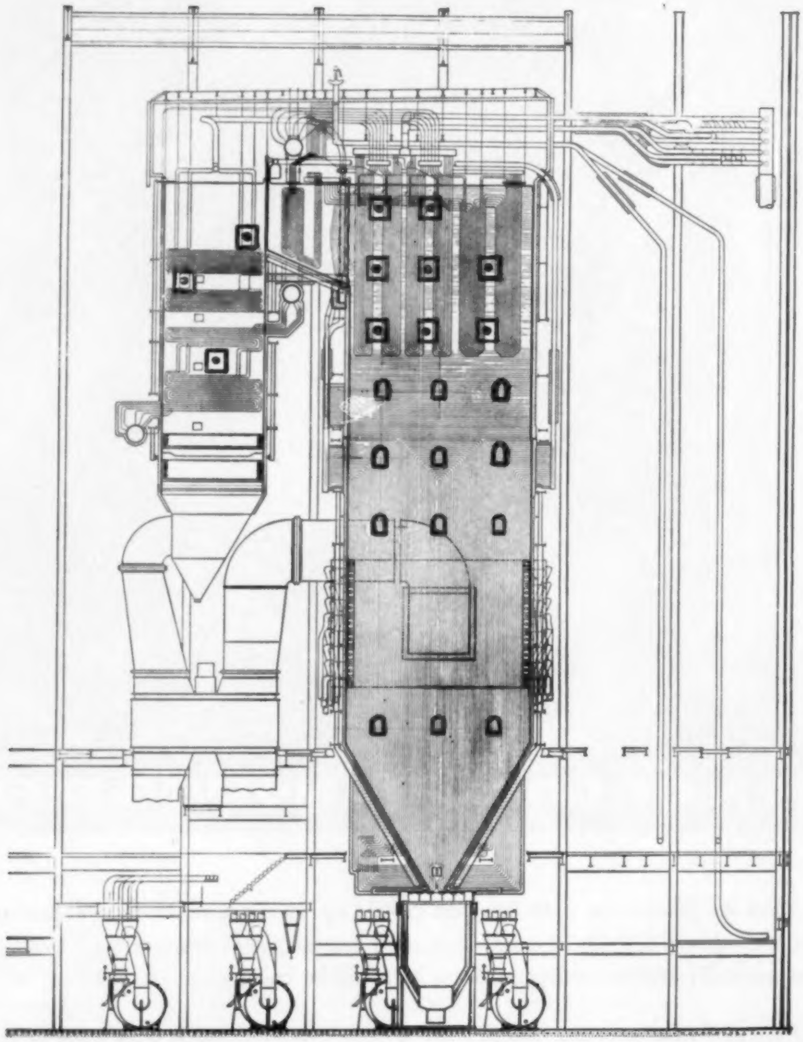
YARNALL-WARING COMPANY
100 Mermaid Avenue
Philadelphia 18, Pa.
Branch Offices in Principal Cities



YARWAY | **COLOR-PORT**

. . . a good way to specify high pressure water gages

It's Vulcan Selective-



PHILADELPHIA ELECTRIC COMPANY, EDDYSTONE STATION, UNIT 1
Capacity—2,000,000 lb/hr at 5000 psig and 1200/1050/1050/F.
C-E Sulzer Monotube Steam Generator

Section shown is of the high-pressure reheat furnace

Sequence for Eddystone Station

Philadelphia Electric's new super-critical steam generators at Eddystone Station will be equipped with Vulcan Selective-Sequence soot blowing systems. Included in the systems for Units 1 and 2 are Vulcan T-30 long retractables with 30- and 37-foot travels, half-'tracts with 19-foot travel from 18-foot permanent extension into the furnace. RW-3E wall deslaggers and air-preheater cleaner controls will also be used.

Selective-sequence control was chosen because it provides positive soot blower operation at proper intervals in precisely the sequence necessary for effective cleaning. The entire blowing cycle will be supervised from a compact, completely pre-wired panel.

Modern Vulcan soot blowing systems, with either automatic-sequential or selective-sequence control, can help keep your boilers operating at peak efficiency. Your Copes-Vulcan representative has the ideas, information and experience to help you choose the system best suited to your needs.

COPES VULCAN

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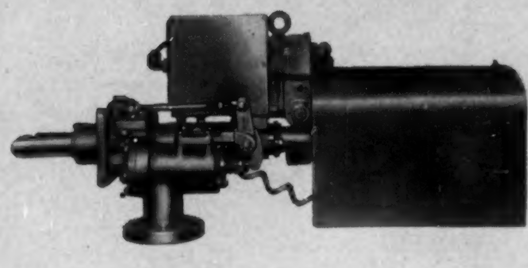
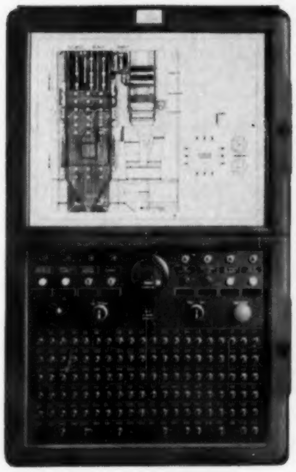
BLAW-KNOX COMPANY

ERIE 4, PENNSYLVANIA

C-V NEWS NOTES



Vulcan RW-3E wall deslagger has dual-motor electric drive. One motor extends and retracts the lance, the other rotates the nozzle. Action is rapid and positive.



Rifle precision, with up to four complete cycles for each soot blower in any pre-selected sequence, is controlled from this completely pre-wired, factory-assembled SSC-120 Vulcan Selective-Sequence Controller. Long retractables and wall deslaggers can be inter-mixed in the sequences. 60-station Model SSC-60 also available.

Bulletin 1030 illustrates and describes the Vulcan T-30 long retractable soot blower as selected for Eddystone Units 1 and 2. Your Copes-Vulcan representative can give you a copy, or write direct to the factory.

PUMP HOUSING is made precisely and accurately from REFRAX® silicon-nitride-bonded silicon carbide. It is used in handling chemical abrasive slurries where corrosion resistance is most important.

Refractories . . . to surpass **metals**

What material combines *all* the following properties? Corrosion resistance so that it is not wet by molten aluminum, and resists attack by most acids; abrasion resistance that prevents wear by both high velocity particles and sliding heavy masses; the ability to withstand temperatures to 3000° F; hot strength so high that at 2450° F its modulus of rupture is 5600 psi?

What material *combines* all these properties? Obviously not a metal, not even a cermet. It is one of Carborundum's special refractories — REFRAX® silicon-nitride-bonded silicon carbide. This material can be precisely formed to tolerances of ±0.005 in./in. with external and internal threads. Finish resembles that of a cast iron part.

Your high temperature problem, no matter how complex it may be, can almost certainly be solved with one of the scores of super refractories by Carborundum. For assistance, write for these three booklets:

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Please send me:

- ☐ Current issue of Refractories magazine on REFRAX®
- ☐ Reprint of article in Product Engineering, Feb. '57 entitled "Nitride-bonded silicon-carbide bridges gap between metals and ceramics".
- ☐ Bulletin on REFRAX®

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Control section of Kellogg's electronic computer.

Electronic Route to Lower Steam Power Piping Costs

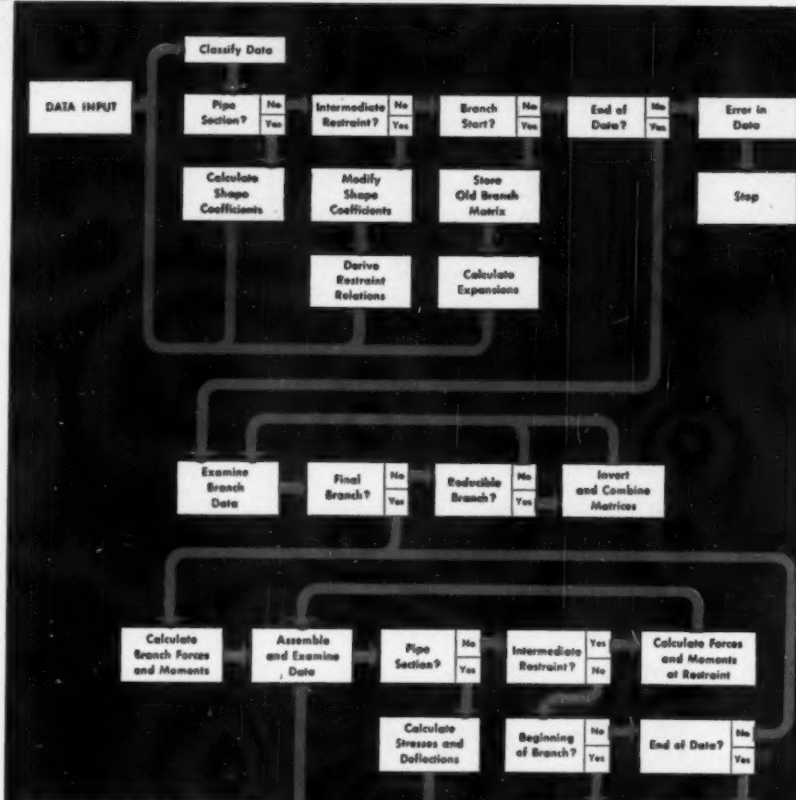
Kellogg's Digital Computer Permits More and Faster Accurate Flexibility Analysis of Complex Main and Reheat Piping Systems

KEEPING PACE with the increasingly critical pressures and temperatures of the modern steam-electric power plant are M. W. Kellogg's advanced techniques for pre-determining stresses and reactions of main and reheat piping. Most recent addition is a large magnetic drum digital computer, used to calculate forces, moments, deflections, rotations, and stresses in complex piping systems.

By enabling Kellogg engineers to undertake a far greater number of calculations in less time than ever before, electronic computation makes possible the ultimate or near ultimate piping system designs. Pipe runs can often be shortened without sacrificing required margins of safety; capital investment and maintenance costs reduced; operating efficiency increased.

A pioneer in flexibility analysis techniques, which include manual calculations, model testing, and a smaller electronic computer, Kellogg continues its pioneering in the power piping industry by the addition of this high speed computer to its New York engineering facilities.

A cordial invitation to see the M. W. Kellogg electronic computer at work is extended to consulting engineers and to engineers of power generating companies and their equipment manufacturers. Appointments may be made through the Sales Manager, Fabricated Products Division.



Computer Flow Sheet

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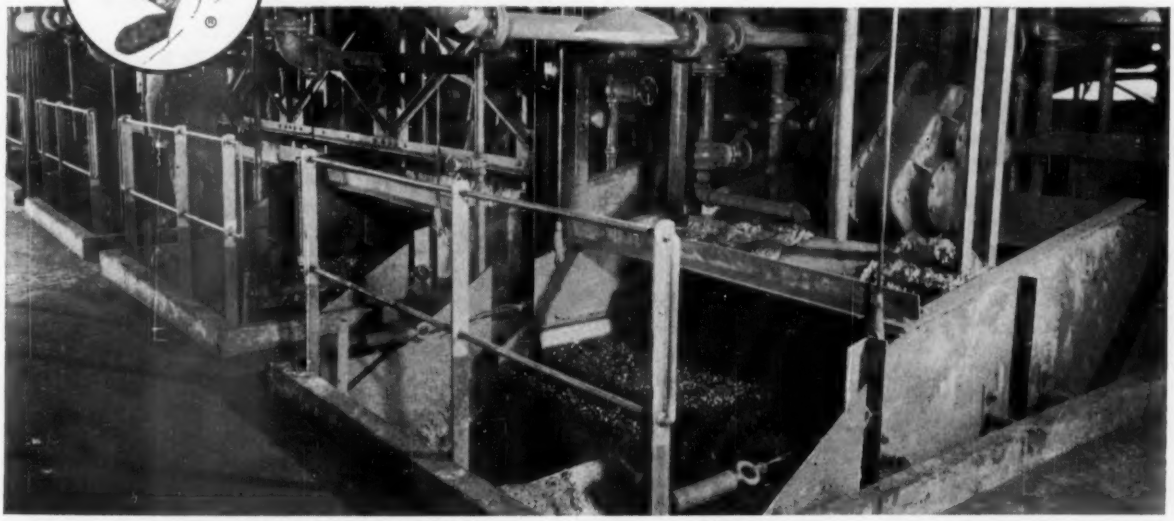

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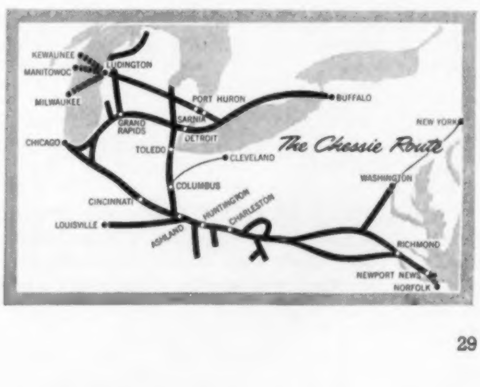

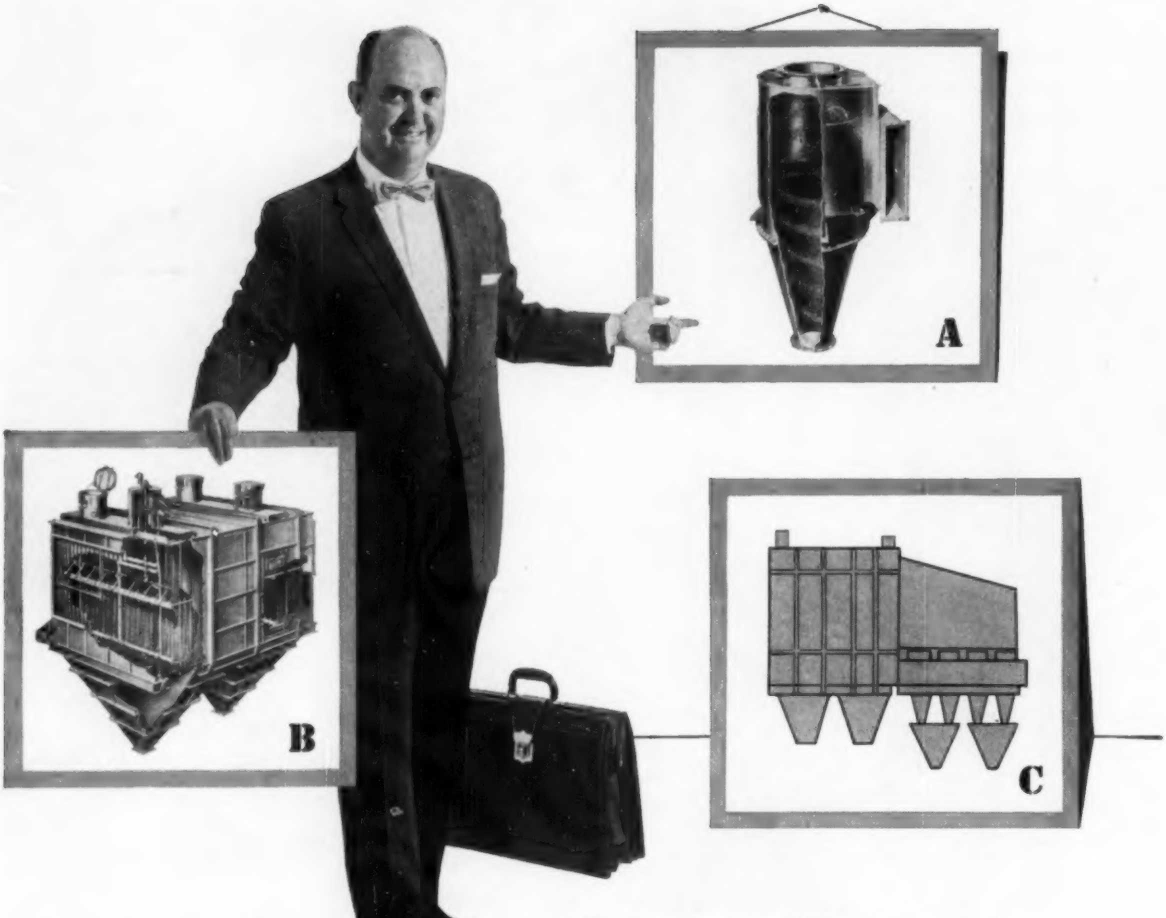

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COMBUSTION

Editorial

Research in the Marketplace

The Fall of the year has become an increasingly important time for the general business economy. It is the period when new budgets are initiated and unexpended funds in present budgets reviewed against projects already underway or planned for the balance of the year. One of the Wall Street columnists refers to this period as the fateful four weeks and points out that discussions about the year's business prospects have not been equalled for so much conflict since 1949. Certainly we all of us, economists or engineers, can appreciate the effect inflation with its attendant high interest rates and high material and wage costs might have upon expansion plans for the immediate future. As a result we find ourselves indebted to the optimistic note carried as a McGraw-Hill Publishing Co. editorial in all of their June 1957 publications entitled, "What Research Means to American Business."

This editorial is based upon the findings in McGraw-Hill's tenth annual survey of Business' Plans for New Plants and Equipment. The point developed is has some new factor been added to change the investment cycle? The authors feel there is such a factor and they submit it is the monies industry is advancing for scientific research and development. They state that altogether industry plans to introduce more new products in 1957–1960 than in any previous four year period. Further, it is their contention that industry plans new processes on a scale that will make much of our present capacity obsolete. Both of these plans are predicated on a marketable product resulting from this planned research program. In summation they foresee a new kind of prosperity for our economy—a prosperity based on deliberate creativeness.

Of course we hope they are right. These editorial writers were quick to state there was no guarantee and that they believed a major problem certainly was the shortage of trained scientists and engineers. We feel, however, the major problem is rather the one so ably singled out by Joseph W. Barker, chairman of the board of Research Corp., before the Annual Meeting and Techno-Sales Conference of Bituminous Coal Research, Inc., in mid-April of this year. We quote "Unless the general 'pumping in' activities of the pure scientists are equal to or greater than the 'draw down' of the development teams, technological progress will grind to a halt some day." If this inescapable fact is known and accepted in the decision to budget for research then and only then we may see this new kind of prosperity.

Labor Day Reflections

The modern steam-electric generating station is symbolic of man's successful efforts to harness increasing amounts of physical power with the assistance of decreasing numbers of men. As another Labor Day passes one is reminded that power generation at one time was literally a back-breaking job. Photos and descriptions of American central stations of the 1880's and 1890's picture delivery of coal by horse-drawn wagons and hand firing of many small boi'ers with men crowding coal in extremely cramped quarters.

Over the years the character of the work has changed about as drastically as the size of the working force. In visiting a modern central station one can walk for a considerable time in areas in which there is much mechanical and electrical equipment but few men. The occasional person one does see gives little evidence of having engaged in arduous physical labor, and he works under conditions that are as safe as his own home and approach it in cleanliness. In fact, the working man in overalls is often out-numbered by instrument technicians, shift and results engineers and the administrative staff.

All of the foregoing reflects itself in more kilowatt output per central station employee. This trend undoubtedly will continue in the future, as our economy requires additional expansion of power generation facilities and new sources of power. And that brings us to another Labor Day observation: finding new power plant sites.

It is somewhat paradoxical that electric power which has contributed so much to the increasing amount of leisure time that all of us enjoy is the source of so much personal and community antagonism when proposals are made to build a steam-electric station on a site that can be construed to have recreational value. It is an unquestioned truism that the modern central station requires large quantities of water for condensing purposes and that such water may equally well be used for swimming, fishing or other recreational pursuits. But it does not follow that a central station has to be a "bad neighbor" or that use and discharge of cooling water necessarily has an adverse effect upon recreation. To meet the increasing demands for power, sites must be found or redeveloped at locations with adequate water, suitable subsurface conditions, and load centers within economical range.

Leisure time and labor-saving devices go hand in hand. To provide the shorter work week of the future will require more power if present standards of living are to be maintained and increased. More power means new power stations, and suitable sites must be found by accommodating both recreation and power generation.

The number and complexity of the individual closed loops comprising a nuclear power plant makes the analog computer an attractive method for solving the system's transient performance problems. The author has employed these techniques on the dual cycle boiling water reactor nuclear plant.

The Analog Computer Aids Nuclear Plant Design*

By DAVID W. LEIBY[1]

General Electric Co.

THE first step in studying power plant transient performance is to break the system down into a number of individual closed loops. These individual loops can then be simulated and analyzed on an analog computer. Next the total simulated system can be interconnected and overall performance obtained.

Various simplifying assumptions need to be made, however, in the simulation of the individual control loops and their interconnection both to limit the complexity of the simulations to the available equipment and also to cover the areas in which detailed information is not immediately at hand such as system phenomena and the various parameters. From the results obtained predictions can be made concerning the general trends in the performance of the power plant for various system disturbances and evaluations may be set upon the importance of system parameters and their individual effect upon system performance. Such information is quite useful in determination of design compromises when certain areas of performance must be sacrificed for other considerations.

The Dresden Power Plant

When the Dresden Nuclear Power Plant came up for consideration the analog computer offered an attractive means of solving certain transient performance problems. This plant is being designed to operate on the dual cycle, boiling water reactor principle. (1, 2, 3, 4).[2] Basically, a portion of the energy is withdrawn from the reactor in the form of high pressure steam obtained by direct boiling within the reactor core, and a portion of the output is taken in the form of a lower pressure steam obtained from a heat exchanger. A simplified block diagram of an early version of the Dresden Nuclear Power Plant is shown in Fig. 1. This block diagram shows the main components of the power plant system as well as the interconnections of the various flow paths of water and steam. The primary recirculating loop consists of the reactor vessel with its reactor core, the risers through which the mixture of water and steam goes to the high pressure steam drum and the steam separators, the primary side of the heat exchanger, and the interconnecting recirculating water lines. The high pressure steam flows either through the bypass valve directly to the condenser or through the primary steam valve to the high pressure stage of the turbine. The secondary steam generated in the secondary side of the heat exchanger flows through the secondary steam valve to an intermediate pressure stage of the turbine. The condensate from the turbine passes through the associated feedwater equipment and then returns proportionally through the feedwater pumps to the secondary steam drum and into the recirculating water loop to maintain proper water level within the various components of the system. The multitude of auxiliary equipment and functions such as blowdown, demineralizers, makeup water, have been eliminated from the block diagram, since their magnitudes and operations are assumed to have insignificant effects upon the transient performance of the power plant during normal operation.

The valves associated with the high pressure steam flow, the bypass flow, and the secondary steam flow are

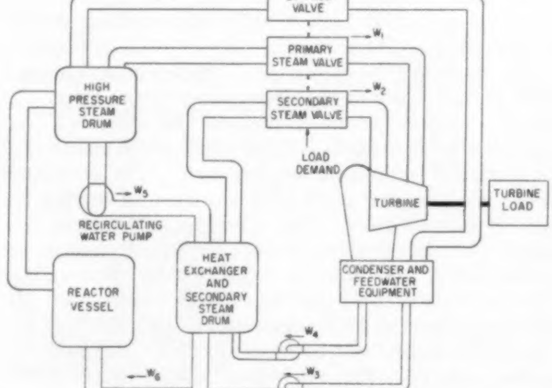

Fig. 1—Dual cycle-boiling reactor power plant

* With the exception of the introductory paragraphs this article was presented under the title "Analog Computer Study of the Transient Performance of a Dual Cycle Boiling Water Reactor Nuclear Plant" at the Summer General Meeting of the AIEE, Quebec, Canada, June 24–28, 1957.

[1] Nuclear Systems Control Engineer, General Engineering Laboratory.

[2] Numbers in parentheses refer to similar numbers in Bibliography at the close of the article.

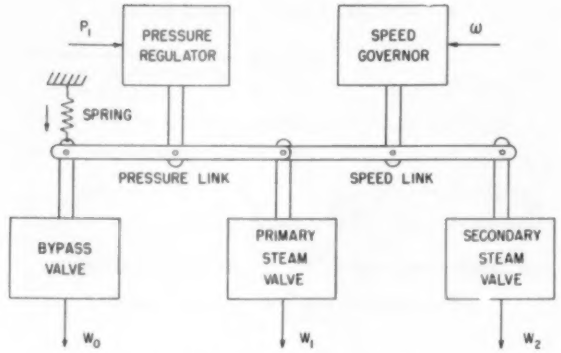

Fig. 2—Steam-flow control

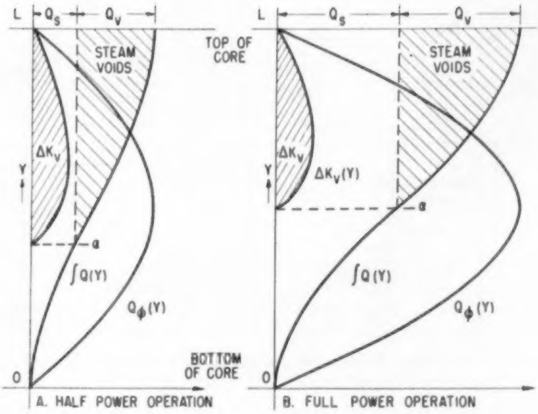

Fig. 3—Reactor void-fraction relationships

interconnected through the mechanical and hydraulic system illustrated in Fig. 2. The error signal between the reactor vessel pressure and the reference pressure operates through a pressure regulator to position the midpoint of the pressure link. The error signal between the turbine speed and the reference speed acts through a speed governor to position the midpoint of the speed link. The secondary admission valve is connected through a hydraulic amplifier to the right-hand end of the speed link, the primary steam admission valve is connected through a hydraulic amplifier to the interconnection between the speed link and the pressure link, and the bypass valve is connected through hydraulic amplifying equipment to the left end of the pressure link. In addition, the left-hand end of the pressure link is restrained by a spring to hold the bypass valve in the closed position.

This unique linkage system provides automatic control of both the turbine speed and the reactor vessel pressure when the power plant is operating into an isolated load. If the load is increased upon the turbine, the speed will tend to droop, causing the speed governor to raise the mid-point of the speed link, thereby opening the secondary steam valve to maintain the proper speed on the turbine. If the reactor vessel pressure tends to increase above the reference value, the pressure regulator will raise the mid-point of the pressure linkage causing the pressure link to rotate about its left end as a fulcrum and the speed link to rotate about its mid-point thereby opening the primary steam valve and closing the secondary admission valve. If there should be more primary steam flow available than required to maintain load on the turbine, the secondary admission valve will become seated and any further demand for more high pressure steam flow will cause the output of the pressure regulator to override the restraining spring, thereby opening the bypass valve to the condenser.

One of the attractive characteristics of a boiling water reactor is its stable operation at constant power when operating under constant pressure.(5, 6) When the dual cycle feature is applied to a boiling reactor it is found that the reactor power level is a function of the subcooling of the water entering the bottom of the core. The term subcooling is used to describe the difference in enthalpy between the water entering the bottom of the core and the saturation enthalpy at the operating pressure. This subcooling of the recirculating water is essentially a measure of the amount of energy being extracted in the secondary steam system plus the energy required to heat the primary steam flow condensate up to the boiling point.

The manner in which the subcooling is related to the total power output of the reactor can be seen by referring to Fig. 3. In this figure, three functions within the reactor core are indicated relative to their positions along the axis of the reactor for two different power levels. If the heat flux density from the fuel elements to the coolant steam, Q_ϕ, (y), is assumed to be sinusoidally distributed along the axis of the core, the energy added to the coolant stream, $\int Q(y)$, has the form of a $(1\text{-}\cos\theta)$ curve. At some point upward through the core, designated as α, sufficient energy has been added to the coolant stream to bring the recirculating water up to the boiling point. All energy added to the coolant stream from that point upward causes boiling within the reactor core. The difference in the abscissa between the total energy added curve and the subcooling value can be considered as an indication of the bubble concentration. The total area beyond the subcooling boundary line gives an indication of the total steam volume within the reactor core. The steam bubbles within the core cause negative reactivity which must be counterbalanced by positive reactivity from the control rods. For the purpose of this study, the negative reactivity from the steam bubbles is considered to be proportional to the integral of the local bubble population times the relative flux level squared. The reactivity from the bubbles or voids, as a function of distance through the reactor, is given by the $\Delta\ Kv\ (y)$ curve with the total reactivity from the voids being represented by the area under this curve.

The two similar diagrams on Fig. 3 are shown for operating at $^1/_2$ rated power level and for operation at full rated power. In the $^1/_2$ power condition, which is shown in Part A, the subcooling is equal to approximately 20 per cent of the full rated output of the reactor, causing boiling to begin approximately 40 per cent through the reactor. It can be seen that if the subcooling is increased, the bubble population will diminish, thereby causing an effective decrease in the area representing the reactivity from the voids. Since this reactivity term is negative, a decrease in its magnitude puts an effective positive reactivity into the reactor, thereby

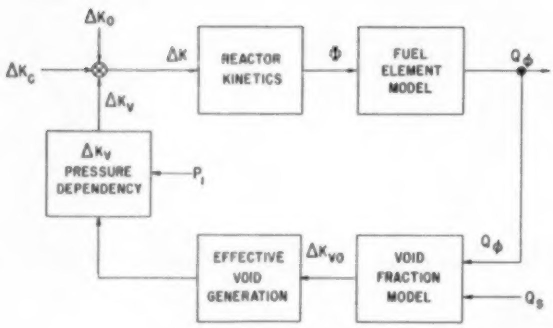

Fig. 4—Reactor void-fraction loop

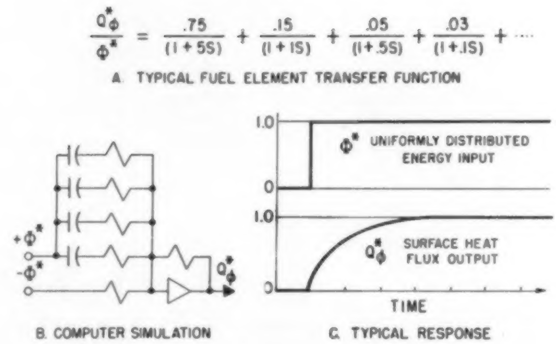

Fig. 5—Fuel-element thermal model

causing an increase in the reactor power as in Part B.

When the reactor is operating at full power as shown in Part B, boiling does not begin until the recirculating water has penetrated over 50 per cent through the reactor. This gives a much shorter region in which the bubbles are present, but, due to the increased magnitude of the bubble concentration, the area of the curve which represents the total reactivity of the voids is the same as that in the conditions shown in Part A of Fig. 3. Since the subcooling of the water entering the bottom of the reactor core, Q_s is essentially proportional to the energy being extracted in the secondary steam system, a method of control of the reactor power level over a reasonable power level range is obtained by changing the rate at which energy is withdrawn from the secondary steam system.

Power Plant Simulation

The presentation of all the details of the derivation of system transfer functions and simulations of all components of the power plant is well beyond the scope of this paper. Therefore, only the block diagrams of the individual loops within the system will be presented along with a discussion of several of the simulation problems involved in each loop.

Reactor-Void Fraction Loop

Probably the most important single control loop within the Dresden nuclear power plant is that which expresses the relationship of the reactor power level, the recirculating water subcooling, and the effective reactivity from the steam voids. This loop, which is present within the reactor core, can be represented by a five element block diagram as shown in Fig. 4. The reactor kinetics represents the relationship between the reactivity, Δk, applied to the nuclear reactor and the output of neutron flux, ϕ. The fuel element thermal model gives the time dependent behavior of the heat energy output at the surface of the fuel elements, Q_ϕ, as a function of the neutron flux level as an input. The void fraction model expresses the relationship between the reactor heat flux and the recirculating water subcooling, Q_s, to give an effective steady state reactivity from the voids, Δk_{vo}. The void generation time simulation block considers the time for the growth of the bubbles within the reactor core and the accumulation of the effect of bubbles as a function of the transport time through the core. The fifth block represents the pressure dependency of the effective reactivity in that, as the reactor vessel pressure, P_1, increases, a given amount of energy in steam will represent a smaller volume of voids within the reactor core. The reactivity from the voids is added with the proper polarity to the reactivity from the control rods, temperature coefficient, Doppler effect, poisons, to give an effective ΔK of zero under steady state operating conditions. The reactor kinetics is simulated in a conventional manner by the use of one operational amplifier with the five delayed neutron groups connected across it and one electronic multiplier to obtain the power level dependency of the reactor gain factor (7, 8).

During the early phases of the study of the Dresden nuclear power plant, the fuel element transfer function was considered to be a simple time constant. During the investigation of the stability of the reactor-void fraction loop, a more refined model of the fuel element was found desirable. An expression was derived for the heat transfer to the coolant at the surface of an infinite cylinder having uniform heat generation throughout its interior. Further improvement of the thermal model of the fuel element was made by considering the thermal impedance present in the bond between the fuel material and the jacket of the fuel element (9). The transfer function for the heat flow across the boundary between the fuel element and the coolant can be expressed as a series of single time constants which can be readily simulated on the analog computer.

The gain constants and time constants in the series expression are functions of the Eigen values of the Bessel functions, the outer radius of the fuel element, the thermal diffusivity of the fuel element material, and the thermal resistance between the fuel element and the jacket. The transfer function of a typical fuel element is shown in Fig. 5, along with its analog computer simulation and the transient response of the fuel element to a step change in uniform heat generation within it.

The transfer function of the typical fuel element indicates that 75 per cent of the energy transfer occurs through a time constant of 5 sec, 15 per cent occurs through a time constant of 1 sec, 5 per cent occurs through a time constant of $^1/_2$ sec, with the remainder of the energy transfer occurring in smaller and smaller parcels through faster and faster time constants. The response of such a transfer function to a step input then shows up with an infinite slope at the beginning of the

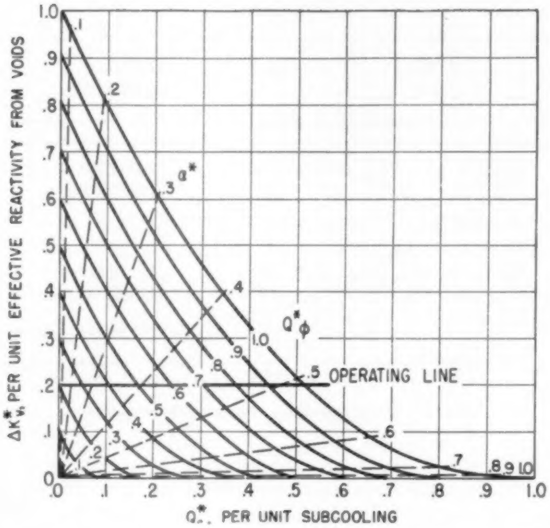

Fig. 6—Calculated effective void map of ΔK^*_v as a function of reactor heat output, $Q^*\phi$, and subcooling, Q^*_s

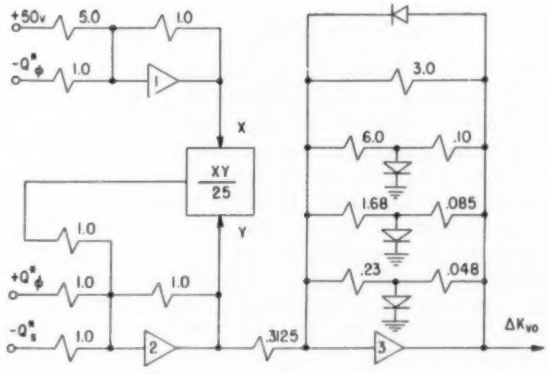

Fig. 7—Reactor void-map simulation

transient which decreases as the effect of the faster time constants disappear and the remaining energy comes from the longer time-constant contribution.

In the simulation of the void fraction model it was necessary to reproduce the calculated effect of the subcooling of the water entering the bottom of the reactor core, Q_s, and the operating level of the reactor, Q_ϕ, upon the effective reactivity obtained from the voids. By means of the geometry presented in the void fraction relationships shown in Fig. 3, an analytical expression can be derived for the effective reactivity of the voids as a function of these two system variables, giving the family of curves as shown in Fig. 6. In this figure, each curve represents a given constant power level, the ordinates indicate values of effective reactivity from the voids, and the abscissae represent values of subcooling entering the bottom of the reactor core. This family of curves, or void map as it is often called, is set up in a per unit system such that for the unit power output curve, unit subcooling causes zero void generation, whereas, zero subcooling causes unit effective reactivity from voids. In the power plant configuration under discussion, the operating line is such that full power is obtained at approximately 50 per cent per unit subcooling. Therefore, the operating line drawn on this family of curves shows that only about 20 per cent of the effective ΔK from voids is present as would be present if the reactor were boiling completely at rated power with saturated water entering the bottom of the core. This family of curves shows that with the operating line at the indicated position, control from 100 per cent power down to approximately 25 per cent power is possible by means of variation of the subcooling.

The behavior of the reactor loop can readily be seen by considering operation about some point on the operating line, say at the 0.8 power position, where the subcooling is approximately 37 per cent. If the subcooling were increased to 40 per cent, the operating point would move down along the constant 80 per cent power line which would cause a decrease in the effective reactivity from the voids, thereby causing the reactor power to increase. The reactor power level will then increase to some value of approximately 85 per cent to bring the operating point back to the operating line. In a similar manner, if the subcooling were decreased down to 30 per cent rated value, the operating point would move upward to cause an increase of about 30 per cent in the reactivity from the voids, thereby reducing the reactor power to approximately 70 per cent to bring the operating point back to the operating line.

This family of curves is simulated on the analog computer equipment, (10) as shown in Fig. 7. An electronic divider circuit is operated on by the subcooling, Q_s, the heat flux from the reactor, Q_ϕ, and by a bias voltage. The output of this divider is a function of the reactivity from the voids. This function is then applied to a function generator which simulates the per unit power curve of reactivity as a function of subcooling. This function generator uses the forward characteristics of silicon diodes and can reproduce the curve with less than 1 per cent error. The simulation of the void fraction map was adjusted to maintain the spacing and the slope of the power curves near the operating line, allowing some deviation at the extremities of the curves. These deviations were not considered serious since normal operation did not cause violent operational departures from the operating line and also because the assumptions made in the calculations of this curve did not warrant the additional effort to obtain a more accurate representation. The results, however, are sufficiently accurate to present a good physical picture of events.

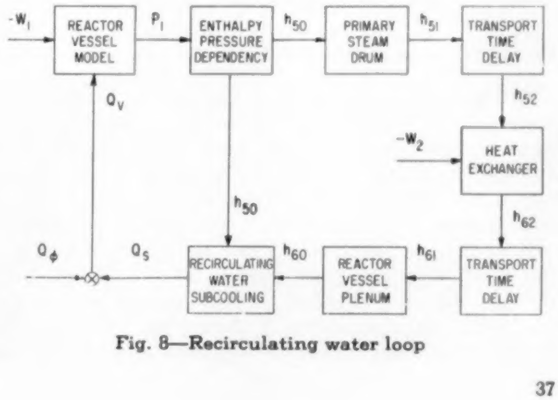

Fig. 8—Recirculating water loop

Recirculating Water Loop

The block diagram of the recirculating water loop, which is shown in Fig. 8, includes eight components. The thermal model of the reactor vessel takes the primary steam flow, W_1, and the difference between the reactor heat rate, $Q\phi$, and the subcooling, Q_s, as the input signals and produces the pressure in the reactor vessel, P_1, as the output signal. The reactor vessel pressure determines the enthalpy, h_{60}, of the recirculating water leaving the reactor vessel. This enthalpy acts through the time constant of the water storage within the primary steam drum and the transport time between the steam drum and the heat exchanger to give an enthalpy, h_{62}, at the input to the primary side of the heat exchanger. The steam flow from the secondary side of the heat exchanger, W_2, produces the heat exchanger secondary steam drum pressure, P_2, and the enthalpy drop across the primary side of the heat exchanger, h_{e2}. This enthalpy drop across the heat exchanger, which is a measure of the subcooling at that point, acts through the transport time between the heat exchanger and the reactor vessel, and the reactor vessel plenum chamber time constant to give the subcooling of the water entering the bottom of the reactor core.

No unusual simulation problems were encountered in this portion of the system. In order to maintain good resolution of the voltages simulating the enthalpies around the recirculating loop, the saturation enthalpy at the rated pressure was chosen as the zero reference. This allowed the changes in the subcooling to cover the full range of output voltage of the operational amplifier. Each transport time was simulated by an all-pass network utilizing three operational amplifiers (11). The heat exchanger was simulated by a relatively simple analysis of the single pass, cross flow, U-tube type configuration (12). A typical response of this portion of the system is given in Fig. 9 in which a step decrease in the secondary steam flow from rated value to zero is applied, such as would occur during a turbine trip-out. The secondary steam pressure and subcooling appearing at the bottom of the reactor are the output functions. The pressure within the secondary steam drum rises approximately as a single time constant whose magnitude is determined primarily by the weight of water stored within the secondary side of the heat exchanger. The subcooling leaving the heat exchanger follows approximately the same curve as the secondary steam drum pressure. It appears at the bottom of the reactor core after being operated upon by the transport time between the reactor vessel and the heat exchanger and the time constant in the reactor vessel plenum.

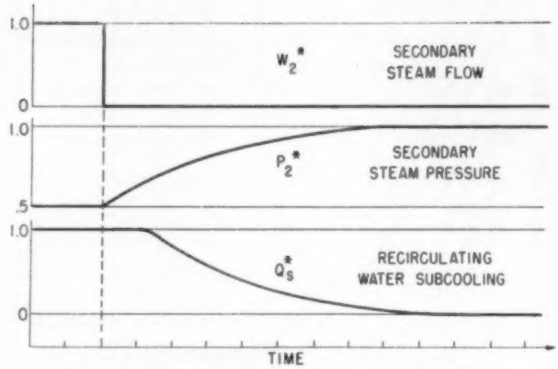

Fig. 9—Recirculating water-loop response

Pressure Loop and Speed Loop

In the preliminary studies leading up to the total power plant simulation on the analog computer equipment, individual studies were made of the pressure loop and the speed loop. In these studies, the transient performance of the individual loops was investigated for a large number of variations in system parameters and for various driving functions. Since the pressure loop and the speed loop are quite closely interconnected, both through the cross-coupling of their control signals and also by an interconnection of their main integrator elements, it is more convenient to present a block diagram of the combined pressure and speed loops as shown in Fig. 10, rather than the individual block diagrams. The pressure loop under normal operating conditions consists of the pressure regulator, the primary steam valve, and the reactor vessel thermal model. The speed loop consists of the speed governor, secondary steam valve, and the steam turbine model.

The steam flow control system contains many more individual elements than those shown in the pressure and speed loop interconnection block diagram of Fig. 10. In many places throughout the system, the power requirements are such that several stages of hydraulic amplification devices must be cascaded in order to obtain proper operation of the system. Also, the system includes auxiliary control equipment such as pre-emergency pressure regulators and special hydraulic mechanisms for obtaining particular operating characteristics of the system. In order to properly simulate the performance of the pressure and speed loops, it is necessary to include the major nonlinearities imposed upon the hydraulic control equipment.

In normal turbine control practice, the oil supply for the hydraulic control equipment is obtained from the same pump that supplies the lubricating oil to the turbine-generator equipment. Therefore, the relatively large hydraulic equipment driving the turbine admission valves and the bypass valve mechanisms must not operate at such rates as to demand a greater hydraulic oil flow than that available from the pumps which would

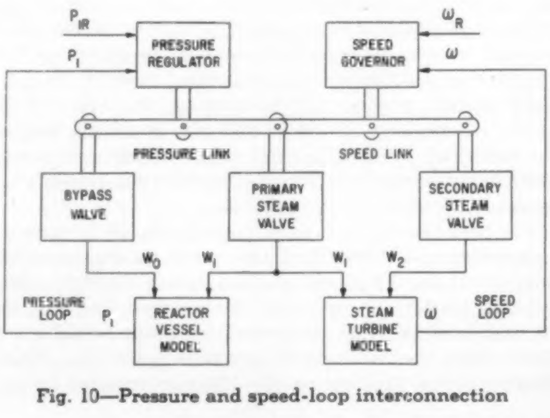

Fig. 10—Pressure and speed-loop interconnection

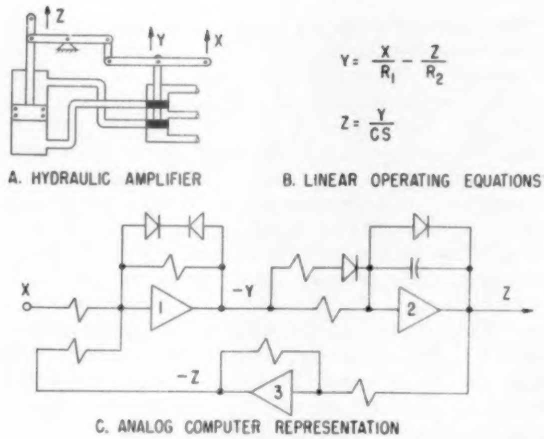

Fig. 11—Hydraulic-amplifier simulation

cause an undesirable pressure drop of the oil system. Since the hydraulic equipment has physical limits upon the strokes such that valves can move no further than fully closed or fully open, it is necessary to insert these limitations upon the simulation of the equipment. Another nonlinearity to include is the effect of the differential areas of the operating pistons of the valve mechanisms, as well as the effect of the static load forces imposed upon the operating pistons.

The analog computer simulation of a typical hydraulic amplifier such as used in the pressure and speed loop representation is shown in Fig. 11. In part A, a very simplified schematic diagram is given of the hydraulic amplifier, showing its three basic components. These components are the pilot valve, the operating piston, and the feedback linkage mechanism. The two expressions describing the operation of this hydraulic amplifier are given in part B of the figure, in which the displacement of the pilot valve, Y, is equal to the displacement of the input, X, minus the displacement of the feedback from the output position, Z, all multiplied by the proper scale factors which are determined by the linkage arm level ratios. The second relationship which holds is that the displacement of the output system is proportional to the integral of the displacement of the pilot valve. This expression is written under the assumption that the rate of flow of hydraulic fluid to the pilot valve is directly proportional to this displacement in either direction of operation.

These two linear operating equations can be simulated by the use of three operational amplifiers as shown in Part C of Fig. 11. The simulation of the first equation is performed on Amplifier 1, the second equation is simulated on Amplifier 2, and Amplifier 3 is used strictly as a sign changer. The output position of the hydraulic amplifier is obtained as the voltage output of Amplifier 2. This amplifier has a silicon diode limiter connected across it in order to simulate the stroke limit of the operating piston. The input to this integrator representing the operating piston is obtained through two adding resistors such that for one polarity of input signal, one resistor alone is in the circuit whereas, for the opposite polarity input, the two resistors are in parallel. This simulates the effect of the static load upon the operating piston. The output of Amplifier 1, which is the position of the pilot valve, is limited in either direction of operation by the two silicon diodes connected across the amplifier. The breakdown voltages of these diodes are selected to obtain the proper rate limits upon the operating piston.

Total System Simulation

The overall simulation of the Dresden nuclear power plant was obtained by the proper interconnection of the various individual control and operating loops. In the final phases of the study, in which several abnormal operating conditions were investigated, up to 70 operational amplifiers, three function generators, and five electronic multipliers were committed to this problem. Since the individual loops and components of the power plant system had been analyzed in considerable detail in the preliminary studies, no great difficulty was experienced in the interconnection of the various loops into the overall system simulation.

In the scaling of the problem for the computer, a non-dimensional form of scaling was used. The electronic multipliers used in this study had scale factors such that 25 volts times 25 volts as inputs gave 25 volts output with a saturation level of approximately 50 volts in the output. Therefore, the problem was scaled so that 25 volts represented 100 per cent rated value of the different system variables in those portions of the problem in which electronic multipliers were required. In other portions of the problem 50 volts was chosen for rated conditions. This adoption of a normalized or a per-unit scaling made interpretation of the data quite easy, in that no unusual scale factors were involved. Also, the adoption of this universal scale factor of either 25 or 50 volts for rated conditions eliminated much of the risk of data being recorded at the wrong scale factor.

The immediate results of this study were obtained in the form of recorder charts of the transient performance of different system variables. Throughout most of the study, ten channels of information were recorded. This was obtained by using an 8-channel recorder with a "Triplexer" connected to the one channel. Since the problem was scaled for real time, the chart speed was sufficiently slow that the "Triplexer" gave a reasonably good indication of the transient conditions. The nine system variables which were recorded for most of the transient runs were the primary steam flow, W_1, the secondary steam flow, W_2, the primary bypass steam flow, W_0, the turbine load demand, Q_D, the actual turbine load obtained, Q_L, the nuclear reactor power level, ϕ, the recirculating water subcooling, Q_s, the reactor vessel pressure, P_1, and the secondary steam drum pressure, P_2. Additional variables which were recorded were the turbine speed, ω, pressure regulator reference, P_{1R}, control rod reactivity, ΔK_c, accident reactivity, ΔK_A, individual bypass valve steam flow, W_{0R}, feedwater flow, W_3, and other system variables. Several hundred transient responses were taken of the power plant performance for a large variety of driving functions. In order to maintain control of the accuracy of the data being obtained, a series of log sheets was set up in which each of the transient runs was given an identifying number, with the log sheet reporting such information as the driving function, the variations in the different system parameters being considered, the recorder calibration for all of

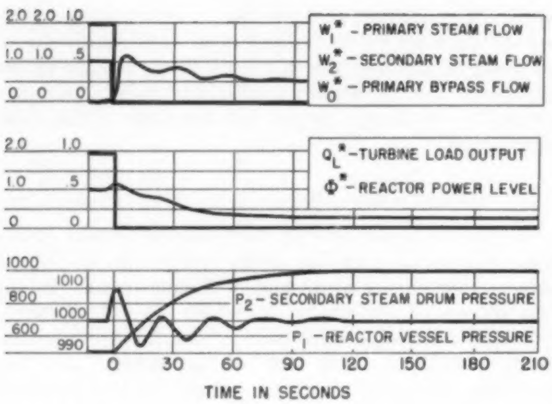

Fig. 12—Transient performance following load tripout

the channels of information being recorded, and the pertinent information being obtained from the recorder chart. From this relatively large amount of data taken, the observed data was presented as families of curves of system performance indications such as transient pressure overshoot or time to reach certain magnitudes as functions of the various driving functions and system parameter combinations.

Indicated Transient Performance

One of the most demanding driving functions which can be imposed upon the power plant, under what are considered normal operating conditions, is the driving function of a power plant trip-out from full load. This trip-out of the power plant can be initiated either by a loss of load on the generating equipment, or by the tripping of the turbine valves by safety equipment associated with the turbine system. The primary consideration upon trip-out is the protection of the turbine equipment from overspeed and also the maintaining of proper operation where possible of the prime power source. The response of the power plant to a turbine trip-out is shown in Fig. 12. At the instant the trip-out occurs, the secondary steam flow and primary turbine steam flow decrease to zero very rapidly. With the time constants of typical control system, these valves shut off in much less than one second's time. The primary by-pass steam flow then increases up to a magnitude to maintain pressure within the reactor vessel. The rate of increase of this steam flow is determined by the rate limit upon the opening of the bypass valve and is so set that there is no detrimental pressure drop in the oil supply system. The turbine load output drops very rapidly to zero following the decrease in the two steam flows. The reactor power level takes a momentary positive overshoot and then decreases to approximately 20 per cent power in the steady state conditions which represent the standby boiling of the reactor with the control rods at the normal conditions. The primary steam drum pressure overshoots approximately 10 psi and then goes through a damped oscillation until the nominal 1000 psi pressure is obtained. The secondary steam drum pressure starts out at the 500 psi value of full load conditions and then increases to the 1000 psi, which gives the same pressure in the secondary steam drum as in the primary system.

The magnitude of the first oscillation of the pressure loop is determined primarily by the magnitude of the steam flow error signal imposed upon it. This steam flow error signal is measured by the rate at which the bypass valve opens following the trip-out of the primary steam valve. From a series of transients in which this rate limit was varied, the curve of positive transient pressure overshoot of the reactor vessel pressure as a function of bypass opening rate is plotted as shown in Fig. 13. This figure shows that a bypass valve rate limit below approximately 20 per cent flow change per second causes an undesirable positive reactor vessel pressure overshoot of over 35 psi. If the valve is speeded up to the magnitude that the limit is effectively removed and its speed is only limited by its inherent time constant, the positive reactor vessel pressure overshoot is held to a value less than 5 psi.

With the bypass valve rate limit set at approximately 60 per cent flow change per second, and the initial power level as a variable, the curve of maximum positive pressure overshoot as a function of the initial load demand preceding the trip-out is obtained as shown in Fig. 14. This shows that the pressure error is practically a linear function of the initial power level before trip-out.

Normal Power Change Maneuvers

Two recorder chart representations are now presented which illustrate the normal maneuvers of the power plant in changing power level at a reasonable rate. In the first case, which is illustrated in Fig. 15, the turbine load

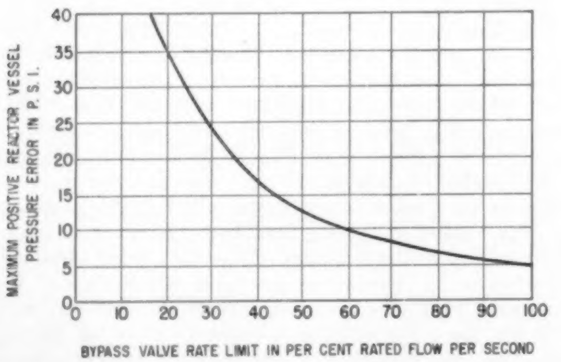

Fig. 13—Effect of bypass-valve rate upon pressure transients

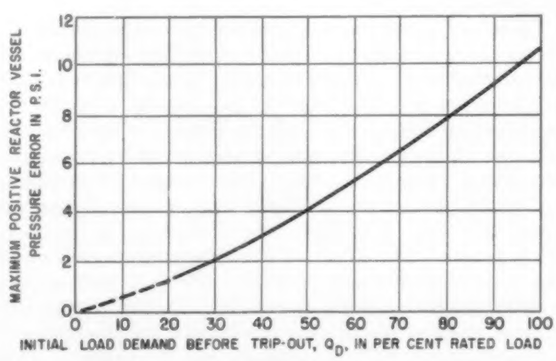

Fig. 14—Effect of tripout level upon pressure transient

demand is increased linearly from zero at the steady state standby condition to 100 per cent in 25 seconds. At this standby condition, the primary steam valve and secondary steam valve are closed; the bypass valve is allowing approximately 40 per cent rated primary steam flow directly to the condenser; the turbine load output is at zero; the reactor power level is at approximately 20 per cent rated power; the reactor vessel pressure is at the rated 1000 psi; and the secondary steam drum pressure is also at 1000 psi.

As the load demand is applied to the turbine control system, the primary steam valve opens to admit primary steam to the turbine simultaneously as the bypass valve closes. At the time that the primary steam valve is carrying all of the primary steam flow, the secondary steam valve begins to open. The secondary steam valve opens at a rate determined by the power demand, and in this particular case reaches its full open limit of approximately 130 per cent. When the secondary steam valve reaches its limit, there is still insufficient primary steam flow to maintain the desired load upon the turbine. Therefore, it can be seen that, at the point where the secondary steam valve hits its limit, the turbine load output deviates from the demand of the 25 second ramp input and does not reach the desired 100 per cent load until approximately 50 seconds after the demand had been initiated. The secondary steam drum pressure does not start to drop until the secondary steam flow is started. Since the recirculating water subcooling does not begin to increase immediately after the secondary steam drum pressure begins to drop because of the transport time delay, the reactor power level does not begin to increase until some time after the initiation of the driving function. This can also be seen from the curve of primary steam flow which remains at practically a constant value until nearly 25 sec after the transient was started. It then begins to increase at a rate determined primarily by the secondary steam drum pressure time constant acting through the recirculating water subcooling to give a reactor power level value. The reactor vessel pressure is found to be only slightly disturbed by this transient, having a maximum positive deviation from the nominal value of about 3 psi and a negative deviation of less than 1 psi.

In the second case, which is illustrated in Fig. 16, the power plant demand is assumed to be changed from 100

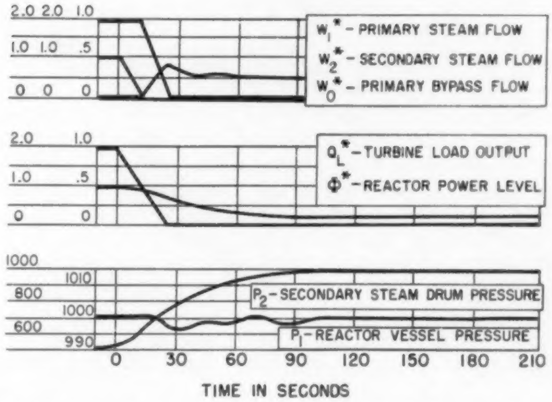

Fig. 16—Transient performance during load decrease from full-load to no-load

per cent to zero per cent load linearly over a 25-sec period. The reduction of turbine load demand causes a decrease in the secondary steam flow. When the secondary steam valve has been completely closed, the primary steam valve is closed simultaneously with the opening of the bypass valve. In this case, the change in the secondary steam drum pressure begins very shortly after the initiation of the transient since the secondary steam flow is the first of the two steam flows to change. The recirculating water subcooling begins to decrease, accompanied by a decrease in the reactor power level. It should be noticed that the turbine load output follows exactly the turbine load demand in going from 100 per cent to zero per cent in 25 sec of time. The reactor vessel pressure shows a negative error of approximately 4 psi with practically no positive pressure error at any time during the transient. After steady state conditions are reached, the reactor operates at slightly above 20 per cent rated power with a bypass steam flow of approximately 40 per cent rated high pressure steam flow.

Individual Bypass Valve Check-out

In the operation of the bypass steam system, the magnitudes of steam flow to be handled are such that one valve is not feasible; rather, a number of valves are operated in sequence. It is estimated that 8 valves will

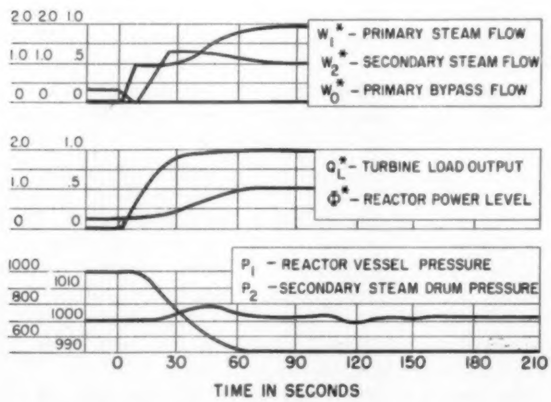

Fig. 15—Transient performance during load increase

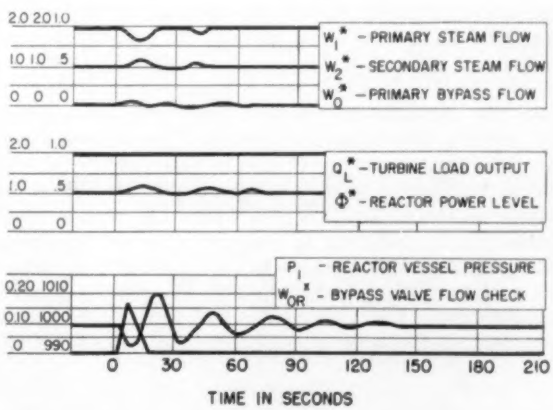

Fig. 17—Transient performance during by-pass valve check

be used, each of which will be capable of allowing 15 per cent rated high pressure steam flow when in the full open position. As one of the operating procedures of the power plant, the operation of each of these individual bypass valves must be checked periodically. Since this will apply a transient to the pressure loop of the system, an indication of the best method of checking of these individual bypass valves is desirable. Each bypass valve is opened at a certain rate, held open for a given period of time, and then closed at one-half the rate at which it was opened. The results of a typical bypass valve flow check is shown in Fig. 17. Under these conditions, the turbine load output remains relatively constant and is not shown on this reproduction of the recorder chart. In this particular case, the power plant is operating at 100 per cent power with rated primary steam flow, rated secondary steam flow, and with no flow through the bypass valve system. The bypass valve is opened in 5 seconds, held open for $2^1/_2$ sec, and then closed in 10 sec. The opening of the bypass valve causes a reduction in the reactor vessel pressure which reaches a maximum negative pressure swing of approximately 8 psi. The bypass flow obtained from this check which first appears as shown in the curve of the bypass flow, causes the pressure regulator to reduce the primary steam flow and thus maintain the reactor vessel pressure. When the primary steam flow drops, the secondary steam flow is increased by the speed governor to maintain load upon the turbine. There is an overshoot of the reactor vessel pressure at approximately this time of the transient, reaching a magnitude of approximately 10 psi above the nominal value. This causes the pressure regulator to open the bypass valve to bring the pressure back to nominal value. There are several cycles of oscillation of the primary steam drum pressure and the three steam flow valves until steady state conditions are reached. It should also be noticed that there is a slight oscillation in the reactor power level.

Since it was desirable to find what would be the best method of checking out the bypass valves with minimum disturbance on the system, a considerable number of runs were taken in which both the rate of opening and rate of closing the bypass valve were varied, as well as the length of time at which the valve was held open. Data were taken for three values of hold-open time of 0, $2^1/_2$ sec, and 5 sec and for rates of valve opening ranging from $^1/_2$ sec for full opening time down to a slow speed of 50 sec for full opening time. The results of this study are plotted as shown in Fig. 18. In those cases in which the valve is opened quite rapidly, the primary driving function is the area under the curve, which is a measure of the total volume of steam withdrawn. It can be seen that the hold-open time is then quite important in determining the magnitude of the positive pressure error. As the rate of opening of the bypass valve is slowed down, the pressure loop is found able to follow the change in steam flow and to maintain the reactor vessel pressure. As the time of opening approaches 50 sec, the pressure error is somewhat less than 2 psi. From all considerations, it appears that an opening time of approximately 5 seconds falls in the region of the largest transient disturbance upon the system's pressure loop.

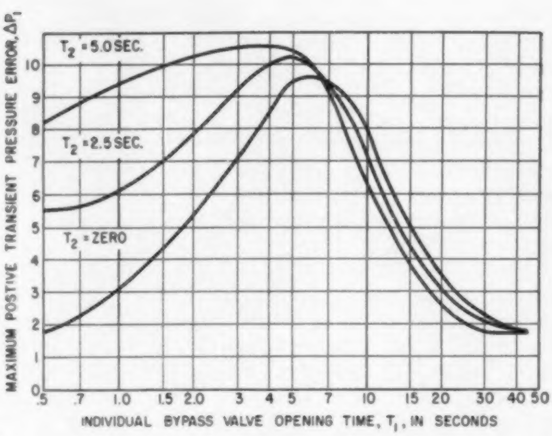

Fig. 18—Effect of by-pass valve checking procedure upon reactor vessel pressure transients

Conclusions

In the previous sections of this paper, the basic theory of operation of the dual cycle boiling reactor power plant has been pointed out, along with examples of methods of its simulation upon the analog computer equipment and several specific examples of transient performances as indicated from the simulation. The primary results of the study indicate the general trends of performance to be expected for the system under the assumptions being made in the analysis. This study is not the final phase of the dynamic analysis of the particular nuclear power plant under consideration but, rather, is a step in the formulation of design characteristics and the understanding of the basic problems involved in its performance. This preliminary study points out several areas in which there is some question as to the assumptions made during the analysis of the system. In particular, two areas are being investigated in further detail for inclusion in a more comprehensive simulation of the system. These areas include a more refined thermal model of the reactor vessel and primary steam drum system in which the effects of the hydrodynamic coupling between the two vessels are included. This system includes the steam storage volumes in the dome of the reactor vessel and in the primary steam drum. These two storage volumes are coupled by a fairly long riser containing a mixture of steam and water which has the peculiar characteristic of being a relatively dense medium and at the same time being quite compressible. The effect of this coupled mass-spring system must be considered in the determination of the total power plant operation.

Another area in which additional information is needed is in the improvement of the reactor-void fraction map within the reactor core. In addition, the representation may become quite complex and include the hydraulic effects of the changing of flow velocities within the core channels as a function of the accumulation of the steam void density. Moreover, it may be necessary to go to a nodal model of the reactor in which both time and space dimensions of neutron flux are considered, rather than the calculated lumped space-time relationship with an assumed time function thrown in to compensate for the assumptions made in the original simulation.

The results of this study show the versatility of the analog computer technique in handling some of the ex-

tremely complex nonlinearities and product relationships which exist in large complex control systems. Although it would be feasible to program this problem for a digital type analysis, much more data appears obtainable in a more reasonable time by using the analog computer techniques. The results are presented in such a form that a good appreciation of the physical picture of the real time performance of the system is obtained. In addition, the analog computer simulation may be adapted to form the heart of a power plant simulator, in which the outputs are used to drive the various meters and instrumentation equipment. Such a power plant simulator can be used as an operator training device so that experience can be gained in the operating characteristics of the reactor power plant long before the actual components are put in operation.

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Editor's Note:

In our August issue we commented editorially, p. 33, "Mechanical Brains," on a paper presented before the ASME in San Francisco, Calif., June 9–13, by G. L. Way, Bechtel Corp., "Computer Applications in the Power Industry," Paper No. 57-A-102, which we feel is a worthwhile reference addition to the above author's bibliography.

Placing A Boiler Control System in Service

By ROBERT W. HUNTER

Copes-Vulcan Division, Blaw-Knox Company

THE primary function of a boiler's automatic control system is to regulate fuel rate, feedwater flow, and combustion air flow so that steam pressure remains constant while steam flow varies to meet load demands.

These regulations must occur in smooth transitions which are balanced and compensated as to rate of change, and with associated component impulses. The secret of obtaining this smoothness of operation lies in making the proper inspections and adjustments as outlined in the photographic sequence taken during the start-up of Unit 5, Seward Station, Pennsylvania Electric Co.

This is a Combustion Engineering controlled circulation boiler rated at 900,000 lb per hour at 2200 psig and 1055 F with reheat to 1005 F. Fuel is pulverized coal. The control system was furnished by Copes-Vulcan Division, Blaw-Knox Company, according to specifications by Gilbert Associates, consulting engineers.

The first step, after all control components are installed, is to make a physical inspection to see that each device is mounted and connected properly. Check each power and control air line from instrument to operator.

From this point on, procedure is to provide (1) remote manual operation, (2) panelboard meter indication and (3) fully-automatic control once boiler operation has been stabilized. Some of the main steps are shown here.

Fig. 1—A good instrument for testing against air line leaks is the sphygmomanometer, a device used by physicians to measure blood pressure. Apply pressure to each line until it is evident there are no leaks. After all lines are checked and purged, apply plant air pressure to the system and adjust for correct supply to each component

Fig. 2—Again using the "sphyg" bulb, stroke each drive unit and valve. Then recheck the stroke from the control panel to assure full range adjustment. The system is now ready for remote-manual control when the boiler is lit off.

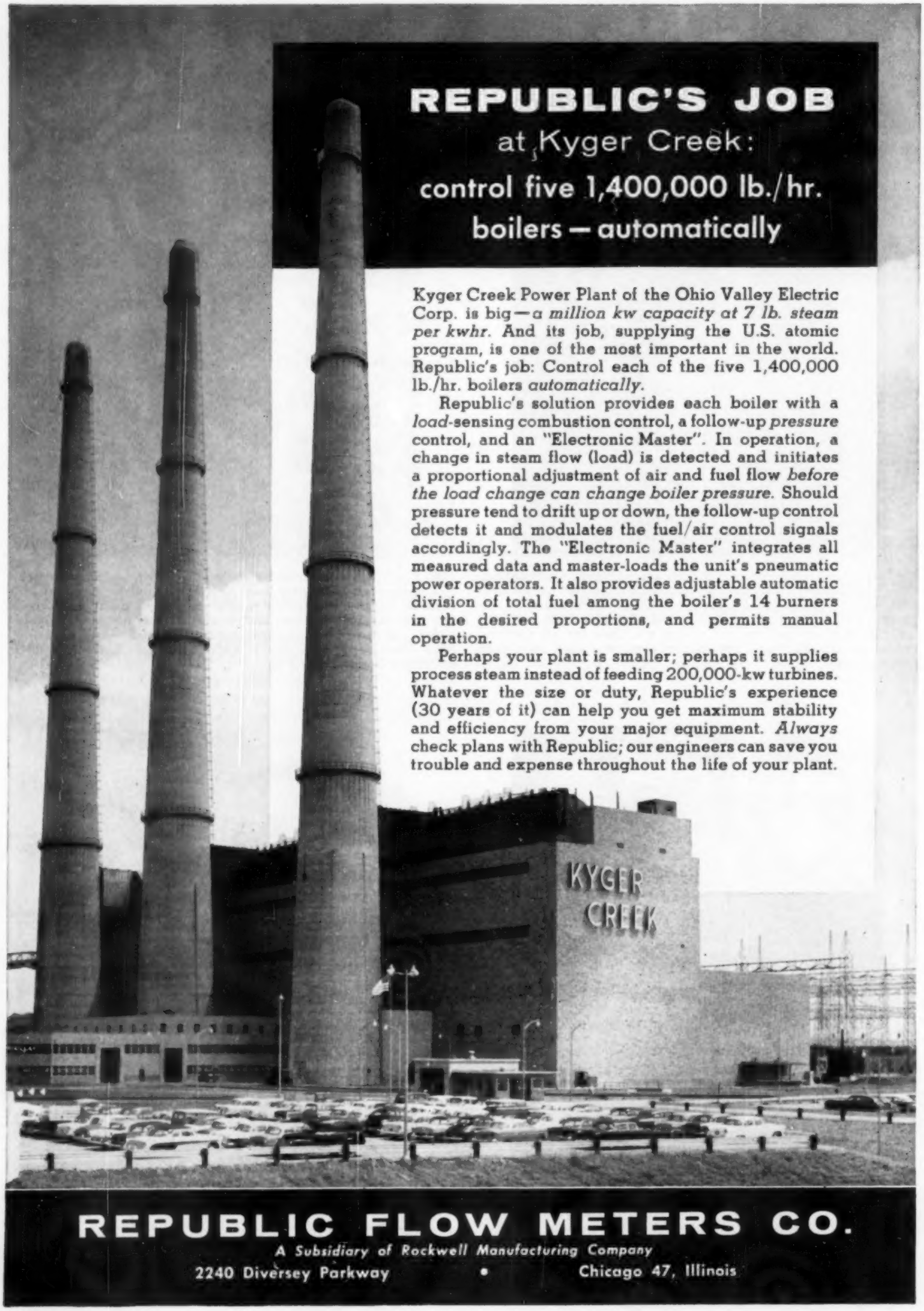
Fig. 3—Check factory calibration and alignment of each steam pressure, steam flow-air flow, boiler water level, etc. instrument, transmitter and receiver to make sure they agree with preliminary engineering data

Fig. 4—Check each controller for proper synchronization. Place temporary settings on the calibrated knobs of the controllers. These settings are established from previous experience on similar installations. At Seward Station, identical Bi-Act controllers and relays are used for all applications to simplify maintenance procedures and minimize spare parts

Fig. 5—While the boiler is being brought up to pressure, the desired drum water level is maintained by manual operation of the feedwater regulating valve from the auto-manual station. When water and steam flows are established, automatic feedwater control is immediately available. Feedwater regulator is a three-influence, instrument-actuated Copes Type 3-L.

Fig. 6—In this plant the "C" pulverizer was the first to be placed in operation. All controls for it were bordered by black tape for the convenience of the operators. Furnace draft is next adjusted for automatic operation and cut into service. The mill circuit is then given preliminary adjustment and placed on automatic control. The same procedure is followed with the remaining mills

Fig. 7—The computing relay serving as the mill master controller is examined and adjusted, then placed in service. Circuit stability is checked for fully-automatic operation. After this complete check the combustion control operated on fully automatic from 100 down to 20 per cent load, and feedwater control down to about 5 per cent at which time the mills were shut down


REPUBLIC'S JOB
at Kyger Creek:
control five 1,400,000 lb./hr.
boilers — automatically
Kyger Creek Power Plant of the Ohio Valley Electric Corp. is big — *a million kw capacity at 7 lb. steam per kwhr.* And its job, supplying the U.S. atomic program, is one of the most important in the world. Republic's job: Control each of the five 1,400,000 lb./hr. boilers *automatically.*
Republic's solution provides each boiler with a *load*-sensing combustion control, a follow-up *pressure* control, and an "Electronic Master". In operation, a change in steam flow (load) is detected and initiates a proportional adjustment of air and fuel flow *before the load change can change boiler pressure.* Should pressure tend to drift up or down, the follow-up control detects it and modulates the fuel/air control signals accordingly. The "Electronic Master" integrates all measured data and master-loads the unit's pneumatic power operators. It also provides adjustable automatic division of total fuel among the boiler's 14 burners in the desired proportions, and permits manual operation.
Perhaps your plant is smaller; perhaps it supplies process steam instead of feeding 200,000-kw turbines. Whatever the size or duty, Republic's experience (30 years of it) can help you get maximum stability and efficiency from your major equipment. *Always* check plans with Republic; our engineers can save you trouble and expense throughout the life of your plant.
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LABORATORY ROTARY COAL SAMPLE DIVIDER

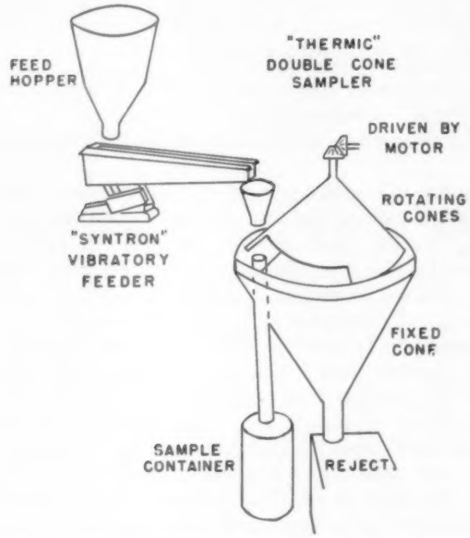

Fig. 1.—Special device enables feeding coal from hopper to point above revolving cones so overflow coal can be caught in a "reject" hopper

Current sampling methods, the authors state, exceed in accuracy the methods of reduction of sample to the quantity required for laboratory analysis. The following report is the authors' experience in conducting tests. Recommendations are made to improve sample preparation accuracy.

By R. L. CORYELL* and F. J. SCHWERD*

Consolidated Edison Co. of N. Y., Inc.

Improving the Accuracy of Coal Sample Preparation

FOR a number of years the authors have been measuring the accuracy of coal sampling methods and instituting methods to improve accuracy.(1)[1] Current sampling methods exceed in accuracy the methods of reduction of sample to the quantity required for laboratory analysis. It was realized that to offset poor precision in the sample preparation a larger number of sample increments would be required to insure results within ASTM tolerance. Hence improvement in the sample preparation for analysis from an error variance of 0.12 to 0.06 would permit taking one-third less increments for the gross sample of a 10 per cent ash coal, thus lightening this burden. Accordingly tests leading to the improvement of sample preparation accuracy have been instituted.

The sample preparation accuracy tests to date have shown the largest errors were present in the riffling of the 4-mesh sample and division of the 20-mesh sample. Review of the work of others indicated that these errors could be minimized by use of a high speed mill and mechanical sample divider.

High Speed Sample Mill

Improvement of the standard three-stage preparation of coal samples has been investigated and the development of high speed hammer mills has suggested a positive means of eliminating the 20-mesh sample division and the slow pulverization operations with ball mills. A Raymond 8-inch Screen Mill was tested at the laboratory and subsequently placed in regular operation.

This screen mill, operating at 3600 rpm, was found to produce considerable quantities of fine dust. To remove this dust a cyclone-type separator was installed on the discharge and has been found to be a satisfactory solution to the dust problem. The maximum quantity of sample handled by this mill was found to be approximately 4 lbs with satisfactory pulverization to 60-mesh size. It was also found desirable to precrush all samples to 20-mesh size in a Sturtevant grinder to insure no +60-mesh size material in the final product and to reduce the pulverizing time.

The screen mill now operates on 20-mesh samples and gives a consistent product with no oversized material requiring "bucking down," as had been the previous practice. However, it is regular practice to pass the product through a 60-mesh sieve to check the condition of the mill's screen. Analysis of the dust from the mill discharge showed the same composition as the sample, thus eliminating the dust separation as a possible source of bias.

Tests also showed that this mill mixed the samples

* Division Engineer and Assistant Engineer, Mechanical Engineering Department.
[1] Numbers in parentheses refer to Bibliography at the end of the article.

thoroughly and consequently it was no longer necessary to mix the samples in a blending machine before removal of the final samples for analysis.

"Thermic" Rotary Sample Divider

The "Thermic" rotary sample divider was developed in England where it was reported (2) to be giving very satisfactory coal sample division. A "Thermic" unit was purchased during 1955 and delivered to the laboratory for test. In this device, shown in Fig. 1, the coal sample is fed from a hopper located above the edge of double cones rotating about a vertical axis so that the coal falling off the cones may be collected in the "reject" hopper. The rotating cones are double slotted so that once in each half revolution the coal falling from the hopper passes through a slot into the sampling pipe below. In this manner two increments are taken every revolution; i.e., 120 increments per minute at 60 rpm rate. The width of the slots can be varied by adjusting one cone with respect to the other to give slot openings from $^3/_4$ inch to 9 inches, collecting, respectively, from two per cent to 50 per cent of the original sample.

To insure a steady flow of the coal sample to the "Thermic" cones at all times, it was found necessary to install a Syntron vibrator feeder between the hopper and the feed pipe above the cones. This feeder has eliminated all the clogging which had previously been experienced with wet coal.

Preliminary tests were made on the "Thermic" sample divider to (1) calibrate the slot openings with per cent of sample retained and (2) ascertain the effect of reducing the width of slot openings on the precision of the sample preparation. These tests showed the per cent retained to be proportional to the width of the slot openings, as shown in Fig. 2.

By adjustment of the slot openings according to the calibration data, samples of 15 to 30 lbs each were divided to give retained samples of 1-$^1/_2$, 3 and 6 lbs. The following results were obtained.

	First Test		Second Test	
	Per Cent of Through-put	Observed Variance	Per Cent of Through-put	Observed Variance
$1^1/_2$ lb retained sample	..	..	4.3	0.0405
3 lb retained sample	16.0	0.0082	10.4	0.0107
6 lb retained sample	33.2	0.0296	22.9	0.0190

These results indicate that the 3-lb sample gives the lowest observed variance and therefore represents the optimum size for the first stage of preparation. The higher variance obtained with the 6-lb retained sample is attributed to the additional riffling operation required to reduce the sample to 3 lbs for the milling operation.

Two-Stage Sample Preparation Tests

Having ascertained the effectiveness of the laboratory screen mill and the modified "Thermic" rotary sample divider, it appeared desirable to test these units in an extensive program under typical plant conditions. The objectives of this program were to obtain the overall precision of sample preparation under the following conditions:

1. Primary crushing to 4 mesh size by either low speed (gyratory) or medium speed (hammer mill) crushers.

TABLE I—SIEVE ANALYSIS

	Low Speed Crusher (Samples 1,2,3,4)		Station Hammer Mill (Sample 5)	
	Average	Range	Average	Range
Per cent on 4 mesh	12.5	11.0–14.0	2.4	1.0–3.3
Per cent on 8 mesh	32.0	30.0–34.0	12.0	9.6–15.5
Per cent on 20 mesh	27.5	27.0–28.0	39.2	38.0–41.3
Per cent through 20 mesh	28.0	25.0–31.0	46.4	39.9–50.0

2. Division of 4-mesh sample to 3 lb. with a "Thermic" sample divider.
3. Pulverization to 60-mesh size in a high speed mill.

Samples of incoming coal shipments were obtained during the period July–September, 1956, at the generating station, and samples prepared in two stages of sample division. Representative primary samples were collected in replicate and subjected to a series of divisions. Primary crushing was accomplished in two ways, namely (1) by low speed Sturtevant crusher and (2) by medium speed American hammer mill. Details of the test program and equipment are in Table IV.

As shown in Fig. 3 five initial samples of crushed coal (4 mesh) were divided to give 3-lb laboratory samples. All these samples represented the same type of coal. Thirty sets of these samples were processed in this manner and a statistical analysis made of the ash content determinations.

Four of the initial samples were crushed in a low speed crusher (200 rpm) and one in the station hammer mill (1800 rpm). Sieve analyses on a limited number of the crushed coal samples show in Table I.

The average sizes (by weight) of the respective crushed samples as determined by arithmetic probability curves were 0.084 inch for low speed crusher and 0.036 inch for the hammer mill. These curves (Fig. 4) confirm the findings of R. A. Mott (3). The much smaller average particle size, due to severe breakage in the medium

CALIBRATION OF "THERMIC" ROTARY SAMPLE DIVIDER

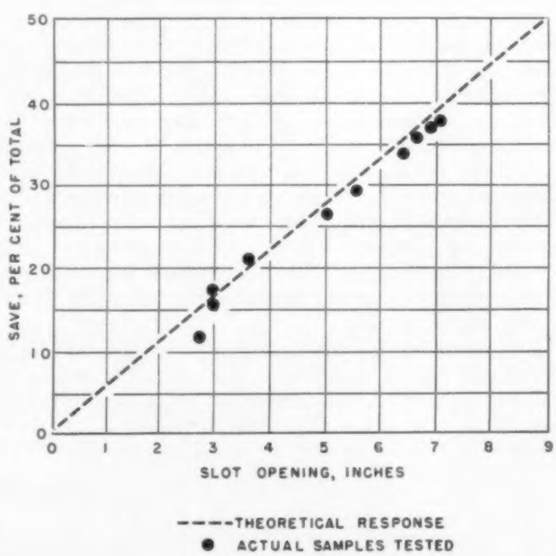

Fig. 2.—Device in Fig. 1 can have the sampling slots of the cone varied in size. Above test indicates per cent of coal retained for sample to be proportional to the slot-opening

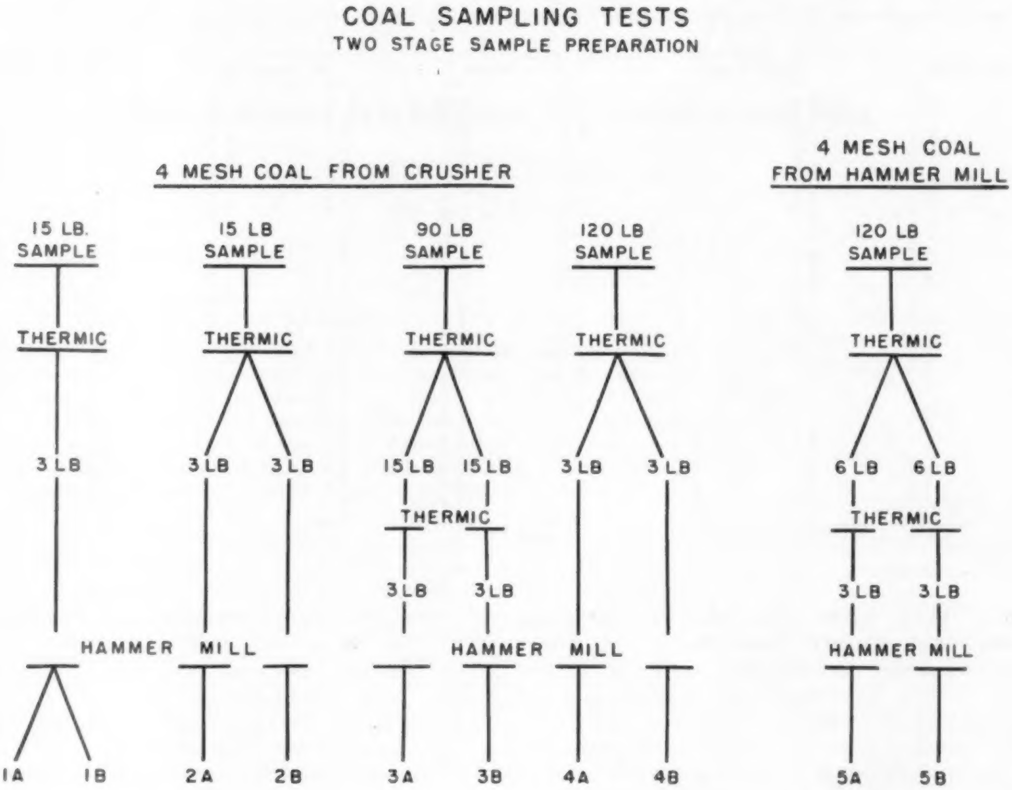

Fig. 3.—Above path of sample flow shows five initial samples of crushed coal were divided to give eventual 3-lb samples

speed hammer mills, would be expected to have a considerable effect on the sample preparation.

A tabulation of the results of this series of sample preparation tests is included, Table IV. One "wild" or "rogue" result (marked with an asterisk in the tabulation) was found in the division of the 15-lb sample to 3 lb. On the basis of the other results of this division and the results of preliminary tests, so great a difference between pairs of analyses has a statistical probability of chance occurrence of less than one in a thousand. This result was therefore discarded in making the final calculation of variance given in Table II.

No bias was found in any of the divisions by the "Thermic." However, there was statistical evidence of a bias in the final riffling of the 60-mesh coal ($F1,29 = 5.97$). The actual magnitude of this bias is not significant for ordinary purposes, the probable systematic difference of the individual pulps from the actual average being only ±0.02 per cent. However, the fact that such a systematic difference exists indicates that riffling is subject to bias, even with very finely divided coals. For high precision determinations or for very high variance coals a small rotary divider would be desirable.

Table III compares the current two-stage sample preparation results with those of earlier three-stage tests. The maximum errors permitted by the ASTM standards are included for reference.

These results show the two-stage sample preparation gives a better precision than any of the three-stage preparations. The comparatively large errors previously obtained precluded use of the ASTM special purpose specification with collection of four times the regular number of primary sample increments. With two-stage preparation the primary sampling requirements may be reduced considerably and still maintain the desired accuracy.

The results of dividing 90–120 lb samples with the "Thermic" unit, as shown in Table II, are particularly

TABLE NO. II—SAMPLE PREPARATION TESTS

Stage of Preparation	"Thermic" Cone Slot Openings, In.	Sample Division, Per Cent	Variance	Overall Variance
Selection and analysis of 60-mesh pulp	..	..	0.0047	0.0047
Division of 15 lb sample to 3 lb	3.5	20	0.0125	0.0172
Division of 90 lb sample to 15 lb	2.7	16²/₃	0.0188	0.0360
Division of 120 lb samples to 3 lb	0.5	2¹/₂	0.0455	0.0502
Division of 120 lb sample to 6 lb, redivided to 3 lb product of station hammer mill)	1.0	5	0.0099	0.0146

TABLE III—TWC-STAGE SAMPLE PREPARATION VS THREE-STAGES

Tests	Stages of Sample Preparation	No. of Samples	Orig. Sample Weight, Lb	Ash Content, Per Cent	Reproducibility, Per Cent Ash (95 Cases Out of 100)	Observed Variance
Con. Edison, 1956	2	30	15	8.0	±0.26	0.0172
Con. Edison, 1954	3	16	20	9.0	±0.48	0.568
Con. Edison, 1953	3	30	15–30	10.4	±0.72	0.1284
Enos (4) 1954	3	30	15	12.5	±0.45	0.0501
ASTM Std. Sampling	3	..	15	10	±1.00	0.25
ASTM Std. Sampling	3	..	15	8	±0.80	0.16

TABLE IV—RESULTS OF TESTS OF "THERMIC" ROTARY DIVIDER—MAIN SERIES OF TESTS—PER CENT OF ASH

4 Mesh from Gyratory Crusher								4 Mesh from Hammer Mill	
15-Lb Sample		15-Lb Sample		90-Lb Sample		120-Lb Sample		120-Lb Sample	
1A	1B	2A	2B	3A	3B	4A	4B	5A	5B
8.3	8.2	8.2	8.1	8.3	8.6	7.7	8.3	7.4	7.7
7.6	7.5	8.1	8.2	7.9	8.2	8.1	7.9	8.4	8.5
8.3	8.4	7.8	7.5	8.3	8.4	8.3	8.1	7.5	7.2
7.5	7.5	7.6	7.4	7.5	7.8	7.6	7.8	7.9	7.7
7.4	7.4	7.4	7.4	7.5	7.7	7.9	7.7	7.7	7.7
7.6	7.4	7.6	7.7	7.7	7.7	7.9	7.8	7.4	7.3
7.1	7.1	7.7	7.5	7.7	7.5	7.8	7.9	8.0	8.0
7.4	7.3	7.6	7.5	7.5	7.4	8.0	7.7	7.3	7.7
7.7	7.7	8.6*	7.7	7.7	7.5	7.9	7.6	8.1	8.3
8.0	7.9	8.0	8.0	7.8	8.1	8.2	8.6	7.8	8.1
7.8	7.9	7.8	8.0	7.8	7.7	8.1	8.0	8.1	8.1
8.2	8.2	8.2	8.3	8.7	8.3	8.4	8.4	8.8	8.7
8.2	7.9	8.1	8.1	8.2	8.3	7.8	7.9	7.1	7.0
8.1	7.9	7.9	7.8	7.7	7.9	7.6	7.9	8.5	8.4
7.7	7.6	7.4	7.5	7.5	7.7	7.4	7.8	7.8	7.7
7.7	7.7	7.2	7.4	8.0	7.7	7.4	7.4	7.5	7.6
7.7	7.7	7.5	7.7	7.8	7.9	8.0	7.2	6.9	6.9
7.4	7.4	7.3	7.1	7.5	7.6	7.2	7.6	7.6	7.6
8.4	8.4	8.5	8.4	8.1	8.5	8.5	8.5	7.3	7.6
8.2	8.0	8.2	8.1	8.1	8.1	8.2	8.3	7.5	7.7
7.9	8.0	7.7	8.0	7.9	8.2	8.3	8.1	7.8	7.9
7.9	7.9	7.8	7.8	7.9	8.2	8.1	8.0	7.2	7.1
8.1	8.1	8.1	7.9	8.2	8.3	8.2	8.1	7.3	7.4
8.1	8.0	8.0	8.2	7.8	7.7	8.0	8.0	7.4	7.6
7.8	7.8	7.8	8.0	8.1	8.4	8.4	7.7	9.1	9.1
7.4	7.3	8.0	7.5	7.8	8.1	7.9	7.9	8.4	8.3
9.2	9.2	9.5	9.4	9.4	9.7	9.5	9.6	9.5	9.4
9.3	9.2	8.8	8.8	9.2	9.0	9.1	8.8	9.4	9.2
8.2	8.2	8.3	8.5	8.6	7.9	9.0	8.5	9.4	9.3
7.6	7.7	7.8	7.6	7.3	7.8	7.9	7.5	9.6	9.5
7.93*	7.88	7.93	7.90	7.98	8.06	8.08	8.02	7.99	8.01

* Omitted from calculation of variance. Probability of occurrence 1:1000.
* Averages.

interesting. These results show that even the poorly crushed samples, with 12.5 per cent on 4 mesh, give a passable precision. The very high precision (0.0099 variance) obtained from the hammer mill product (2.4 per cent on 4 mesh) indicates the importance of having the sample crushed as fine as possible at the first stage.

The principal advantage of two-stage sample preparation, however, is the reduction in laboratory work. Table V compares the sampling handling procedures for three-stage and two-stage preparation. For three-stage preparation nine steps are required with the possibility of errors in each step. Two-stage preparation requires only five steps and eliminates riffling in all but the last one.

Conclusions and Recommendations

Based on the results of these tests of two-stage sample preparation the following conclusions and recommendations are offered.

1. The high speed mill effectively pulverizes a 3 or 4-lb sample for division to a final sample.
2. The rotary sample divider effectively divides samples of 4-mesh coal to samples as small as 3 per cent of original.
3. Mixing of the final sample is not necessary when pulverized by high speed mill.
4. When using the rotary sample divider and high speed mill the number of laboratory operations for sample preparation is halved.

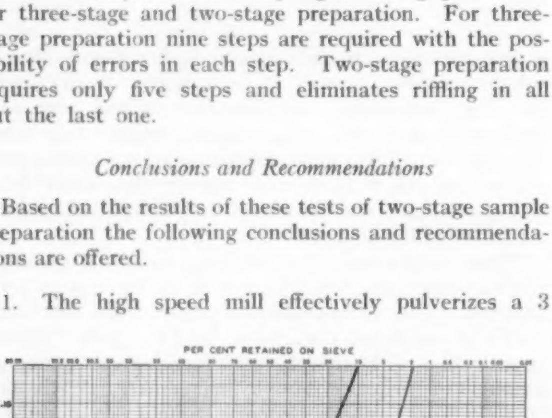

Fig. 4.—Average size by weight of samples resulting from rotary crusher preparation for four examples in contrast with one prepared by a hammer mill

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TABLE V—COMPARISON OF THREE-STAGE AND TWO-STAGE COAL SAMPLE PREPARATION PROCEDURES

	Three-Stage Preparation, 15–30 lb, 4-mesh Sample		Two-Stage Preparation, 15–30 lb, 4-mesh Sample		Two-Stage Preparation with R.S.D., 15–30 lb 4-mesh Sample	
I	*Riffle* twice	(2)	*Riffle* twice	(2)	*Rotary Divider*	(1)
	Crush to 20-mesh	(1)	*Crush* to 20-mesh	(1)	*Crush* to 20-mesh	(1)
II	*Spoon* Out 200 grams	(1)	*Screen Mill*	(1)	*Screen Mill*	(1)
			Riffle	(1)	*Riffle*	(1)
			Spoon Out 25 grams to analyst	(1)	*Spoon* out 25 grams to analyst	(1)
			Total Operations = 6		Total Operations = 5	
III	*Ball Mill*	(1)				
	Riffle	(1)				
	Screen & Buck to pass 60-mesh	(1)				
	Mix on Mixing Wheel	(1)				
	Spoon Out 25 Grams to Analyst	(1)				
	Total Operations = 9					

Servomechanisms in Combustion

By JOHN S. TYNDALL

Electrical Engineer

Part III of a Series

Advantages and limitations of air as a control fluid in a servomechanism are listed and described. The transmission factors associated with pneumatic signals are discussed, including the pressure range used and the speed of transmission. Typical oil-operated and air-operated servomechanisms for controlling the heavy damper of a boiler stack are shown, together with the relative advantages and disadvantages of each type. The design problems for air-operated power units are discussed, including high-inertia loads and damping.

THE term "servosystem" refers to a mechanism whereby a power-amplifying device is regulated by the error or discrepancy between a controlled variable and the controlled point. A servomechanism in a continuous control system is a closed loop system—that is, a system in which the difference between the actual control point and the desired control point is the error signal, which continuously controls the mechanism. The military services have made remarkable accomplishments in the field of closed-loop servosystems. Although the specifications and conditions with which combustion engineers are concerned differ widely from those of military engineers, the developments by the military are of great importance to combustion engineers.

A servomechanism compares two quantities or conditions and develops an error signal that drives the mechanism. The error signal and driving signal can be electrical, hydraulic, or pneumatic. This paper discusses the factors associated with the use of pneumatic systems—that is, systems which use air as a control fluid.

Advantages and Limitations

The principal advantages of air as a control fluid are:

1. Air is a low-cost, consumable, fireproof fluid requiring no return piping.

2. For continuous signal transmission, especially in multiple-loop systems, air is unexcelled for moderate transmission distances. Compared with modulated electrical-signal systems, the receiving and transmitting servos are simple and inexpensive. This advantage is so well recognized that present-day oil and electrical systems use air signal-transmission extensively.

3. Air power units ordinarily have a lower ratio of inertia to peak thrust than geared electric drives.

4. Air power units have certain practical advantages over oil units. These advantages are due to the fact that an elastic fluid is used for prime-mover power generation. As power-cylinder work is done by fluid pressures and volumes, the mass flow of air is smaller than that of oil for the same volumes and pressure levels. Pressure drops in pipes are proportional to the square of the volume flow and the fluid density. Thus, high volume flows give much lower pressure drops for air, which has a lower density than oil. This means smaller lines, smaller relay systems, and smaller valve porting. Hydraulic accumulators are often uneconomical and cumbersome, and the hydraulic pumping is continuous whether the power units are consuming fluid or not. Compressed-air receivers, on the other hand, are advantageous and practical.

The principal limitations of air as a control fluid are:

1. The necessity for a reliable, weather-protected air supply requires a well-engineered compressed-air supply. Indiscriminate use of ordinary plant air supplies has been a factor in past disappointments.

2. For high-speed control applications, especially where long lines are involved, the capacitance characteristics of air transmission can be a limiting factor. For such applications, systems operating at high pressure levels and having large air-handling capacities are required. Transmission lines must be terminated by devices of negligible volume. In certain cases, newly developed electro-pneumatic transmission links can replace excessive lengths of air line.

3. Air lacks the high inherent damping and lubrication characteristics of oil. This must be overcome, especially in the design of power units.

Transmission Characteristics

Pressure Range—Combustion systems for transmission of pneumatic signals make use of numerous pressure levels. The ISA (*Instrument Society of America*) recommended standard of 3–15 psi is in wide use. However, both higher and lower pressure systems are in extensive use for signal transmission. The highest pressure-range in wide use is about 0–60 psi, the lowest in use is about 0.5 psi. Inverted ranges, such as 60–0 psi, are also employed widely, principally to give receiver devices an inverted direction of motion for increasing signal. The advantages of a biased transmission system, such as 3–15 psi, result from the fact that the low end of the range is not at atmospheric pressure level. However, the disadvantage of a biased system is the more complicated system required for combining signals and handling the bias pressure.

Speed of Transmission—Although an air transmission-line is analogous to a resistance-capacitance transmission element, the line has characteristics

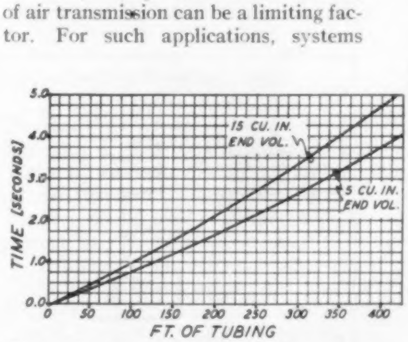

Fig. 1—Time constant of a 0.25-in. pneumatic transmission line with two end volumes.

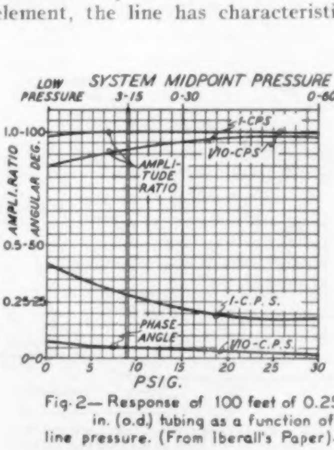

Fig. 2—Response of 100 feet of 0.25-in. (o.d.) tubing as a function of line pressure. (From Iberall's Paper).

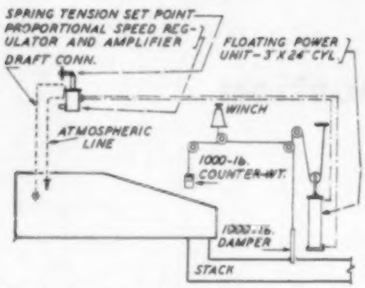

Fig. 3—Hydraulic boiler damper control.

which depend on the pressure level. Air is like a spring whose "stiffness" increases with the pressure. Also, the flow and resistance characteristics are linear over only limited intervals. Thus the response characteristics of a line to a step variation in input depend on the magnitude and location of the step variation. Fig. 1 illustrates the time constant (time for impulse to reach 63 per cent of its final value) for various lengths of 0.25-in. (O.D.) copper tubing with two end volumes. A 0–15 psi step input was used.

A recent paper by Iberall[1] of the Bureau of Standards, has remarkably improved the quantitative analysis of air lines by using a frequency-response approach to the problem. This paper solves the problem of expressing an air transmission-line as a graphic transfer-function which is bounded by pressure level and valid over a limited disturbance range. Fig. 2 was derived from Iberall's paper to show the influence of transmission level on the design of controls. A 100-ft length of $^3/_{16}$-in. (I.D.) tubing was assumed to be terminated by a negligible volume. A sine-wave input of small amplitude about a mean pressure level is understood. The attenuation and angular lag of the output pressure-wave are plotted against the mean pressure for frequencies of one cycle per second and one cycle in ten seconds. It is evident that the use of high-pressure transmission results in less attenuation and less angular lag—that is, fast control around the control point.

The speed-of-response requirements of a servomechanism depend on the process response. Theoretically, a process can be made to respond as fast as desired by the application of high energy at high rates to the process. In practice, however, limitations always occur. For example, in an oil-fired steam-generator, rapid changes of boiler temperature can be produced only by fuel-firing rates which are destructive of the lining. Limitations on energy supply rates exist in every physical installation.

When it is desired to drive a given process at higher recovery rates by means of an automatic control-loop, the attending increases of phase-angle lag in the process make it essential for control-circuit delays to be small.

The important subject of frequency response and speed of air-control devices is one with many ramifications. A great variety of these devices is available, including practically every kind of signal converter. Computing elements which perform algebraic and functional operations, including linear multiplication and division of signals, are available both as specialized components and as combination devices. (See section covering Pneumatic Relays.) Program and other types of input devices are available also. The application of these devices in multiple-loop circuits is rapidly gaining headway in industrial process control, and will be covered here.

Heavy-Damper Controls

A typical oil-operated control for a boiler furnace-pressure, stack-damper is shown in Fig. 3. The block diagram of the system is shown in Fig. 5. The slide damper is a water-cooled steel and brick structure, which operates with loose guiding. Such dampers can weigh about 4000 lbs and have dimensions of 6 × 8 ft. A counterweight system ordinarily is employed to relieve the manually-operated winch of dead-weight.

The power unit must be able to move the damper through its full 6-ft travel, although in practice full opening seldom is required.

The oil-operated control system of Fig. 3 uses a double-reeved cylinder having a bore of 3 in. and a stroke of 24 in. This cylinder is powered by a proportional-speed oil controller and relay, with a capacity of 12 gpm, at 100 psi.

The cylinder displacement is about 450 cu. in. At a maximum flow of 12 gpm, or 2800 cu. in. per min., the minimum time for full stroke is 25 sec. Thus the maximum piston speed is 56 in. per minute, which occurs at no load on the cylinder. The product of piston area and 100-lb oil pressure gives a peak thrust of 1250-lb force. This is the stalled thrust of the cylinder, or the zero-speed thrust characteristic.

The damper weight of 1000 lbs usually is balanced by an equivalent counterweight so that the inertial system consists of a mass of 2000 lb. The system is double reeved so that the 2000-lb mass during acceleration appears to the cylinder as though an 8000-lb balanced mass were connected directly to the rod.

The controller is a proportional-speed regulator which establishes a rate of oil flow proportional to the difference between the furnace pressure and the regulator setting. The full range of operation is usually about 0.2-in. water. The limiting control speed usually is established by the cylinder oil consumption. The oil cylinder requires full-time pump operation, the oil being bypassed when not used by the regulator.

The air-operated counterpart of this hydraulic system is shown in Fig. 4. Fig. 6 is the block diagram of the pneumatic system. This system uses a 6-in. × 36-in. positioning air cylinder. The no-load traversing time is 10 sec.

The boiler-pressure converter changes furnace pressure into an air-pressure signal between 0 and 30 psi. This signal is fed into a *ratio totalizer regulator*, the set point of which is adjusted pneumatically from the control panel. A proportional-plus-floating response is transmitted to the air servo, which has a type of rate action superimposed when

[1] "Attenuation of Oscillatory Pressures in Instrument Lines," by Arthur S. Iberall, *Journal of Research of the National Bureau of Standards*, RP2115, Vol. 45, July 1950.

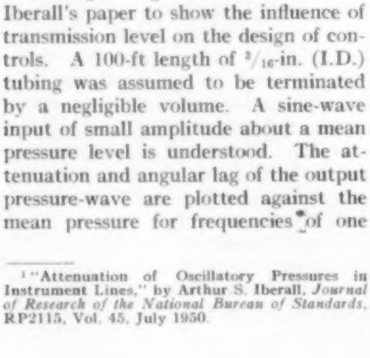

Fig. 4—Modern servosystem illustrating an air-operated damper-pressure unit.

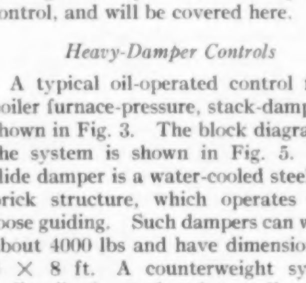

Fig. 5—Block diagram of hydraulic boiler damper-pressure control.

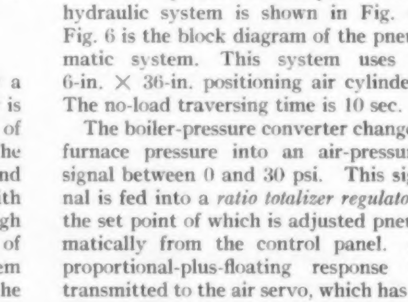

Fig. 6—Block diagram of servo-pneumatic boiler unit control of damper-pressure

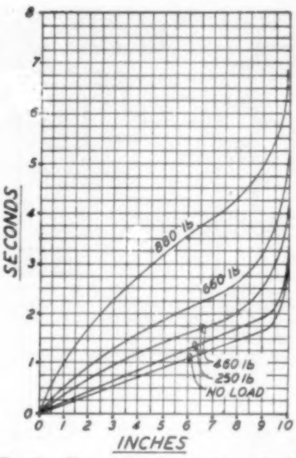

Fig. 7—Traverse-time characteristic curves for a servo-pneumatic power cylinder with various loads.

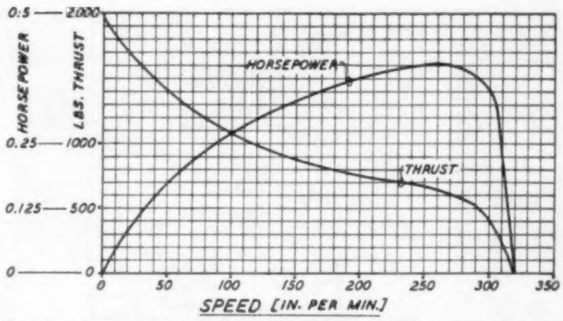

Fig. 8—Curves of thrust and horsepower plotted against speed.

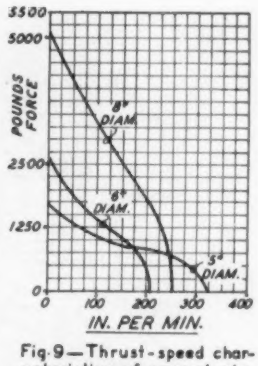

Fig. 9—Thrust-speed characteristics of several air servos with 100-psi. air.

desirable. The control sensitivity is better than 0.001-in. water.

The air control is about twice as fast as the comparable oil control in operation. However, the air system uses more complicated apparatus than the oil system. The faster response introduces a major inertial problem, which was minor in the slower oil system. Two major benefits result—(1) a non-inflammable and cheaper control fluid is used, and (2) the control response during transients is improved greatly.

Power Units

As early air cylinders proved inadequate for handling heavy inertial loads which were combined with stickiness, it was felt by many that a power unit operated by an elastic fluid was inherently a poor device for heavy work. Instability of a power unit under an inertial load is an unpleasant experience. Big dampers build up fairly fast oscillations without warning. When this happens, the cylinder acts as though it had been taken charge of by the damper. The term "chugging" has been used to denote this situation.

Five years ago many thought that the advantages of compressed-air systems—high control speed and freedom from hydraulic-fluid troubles—were doomed by the stability limitation. Further, frequent minor maintenance on air cylinders was annoying even though it was realized that a single bad leak on a liquid system usually resulted in very important maintenance expenditures and production losses. However, it can be said today that air-operated power units are now well established in the industry. The inertial load-stability problem has been solved by relatively recent cylinder design and application techniques.

The Inertia Problem—Fig. 7 is a set of characteristic curves of a 5-in. × 10-in. positioning, air-operated, power cylinder, using 100-psi air. Piston displacement and time are plotted for suddenly applied full-range positioning inputs to the cylinder, which is lifting weights. The linear sections of the curves correspond to steady speed. For this condition, the piston thrust is determined by the attached weight and the lever arm.

Fig. 8, which is plotted from the steady-speed data of Fig. 7, gives a typical cylinder-thrust vs. speed characteristic. The curve of useful horsepower output is shown also in Fig. 8. As thrust increases, speed decreases.

A load with sufficiently high inertia can cause instability of any type of positioning servo—pneumatic, hydraulic, or electric. The attachment of a proper oil-dashpot (viscous damper) to the output shaft restores stability.

Damping—The effect of the output damping of the dashpot is analyzed easily. The resistance of the dashpot increases directly with the piston speed. Thus the thrust applied to the inertial load is less at a given cylinder speed by the amount absorbed by the dashpot. In other words, the automatic decrease of thrust applied to the inertial load as piston speed increases accounts for the stabilizing factor.

The damping is controlled by the dashpot force-speed constant. This constant is adjustable by a needle valve in the dashpot. In practice, no dashpot is necessary because the same effect is obtained by cylinder design.

As shown in Fig. 8, the speed-thrust characteristic of the cylinder displays the general damping characteristic of a constant-thrust device with a dashpot. However, as the slope is a built-in characteristic of a particular cylinder design, it is not adjustable.

Assuming that the present upper limit of the air supply is 100 psi, the damping curve can be made more steep and the peak thrust can be increased by increasing the cylinder size, as shown in Fig. 9. Air cylinders in general have somewhat larger bores than oil cylinders. Nevertheless, the practical operating speeds are higher than for oil.

The ratio (N) of the damping actually present to that required for critical damping is a function of the dimensionless parameter $F/S \times T/M$, where F/S is the actual thrust-speed characteristic slope, T is the no-load cylinder traversing time, and M is the inertial mass.

Air cylinders can be designed to have high-speed, inertial-load stability, and good characteristics with "sticky" loads.

Combustion engineers are now using pneumatic control apparatus where it meets the requirements of their particular field. Study of the principal limitations of air as the control fluid gives background to the extensive use of high-performance air-operated systems. Without doubt, the continuing technical advance in this control field will be paralleled by advances in competitive systems. It is by this endless competitive process that free industry assures itself of the leadership accruing to the wisdom of the open mind.

Pneumatic Force Bridge Relay

Typical of the several precision-type air relays recently developed for the control of servomechanism loops is the Sorteberg[2] Force Bridge shown in Fig. 10. This is a computing device. It can convert a transmitted signal from a square-root flow meter into a lineal signal, permitting the use of a flow receiver with an evenly-graduated chart. The design of the force bridge assures friction-free operation by use of the feedback principle in a unique weighbeam and fulcrum system. The principal components are of plug-in construction, housed in a rugged, cast aluminum case. The following are some of the operations of this unit for servo systems:

Fig. 10a. Square root extraction in converting a pneumatic signal from a square root flow transmitter into a

[2] Sold through Minneapolis-Honeywell Co.

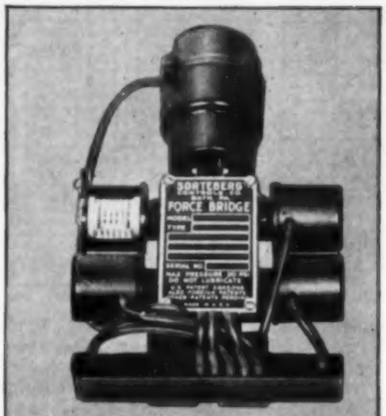

Fig. 10—Interior of Servo Force Bridge showing principal components of pneumatic circuit.

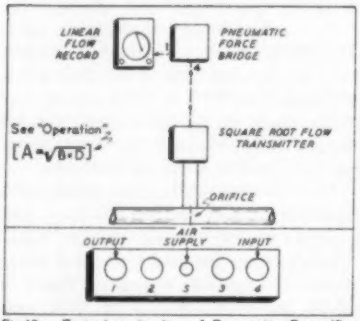

Fig. 10a—Typical application of Pneumatic Force (Servo) Bridge. The bridge converts a pneumatic signal into a linear output, a square root extraction. See Figs. 10b through 10g for additional applications.

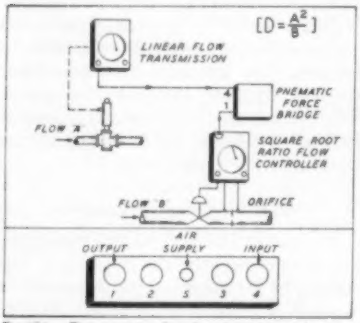

Fig. 10b—The squaring function to obtain ratio control of two flows where one is measured by a linear flow meter, the other by a square root meter. Force bridge supplies a squared signal to the flow ratio control.

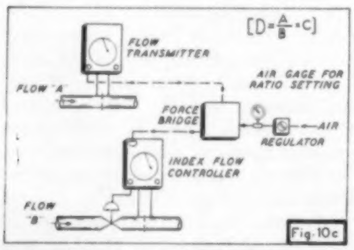

Fig. 10c—Ratio setting function of Bridge. By means of a manually operated pressure regulator, an air signal is used to vary the relationship between input and output pressures. The input signal is multiplied by signal from the regulator, and the product is the output.

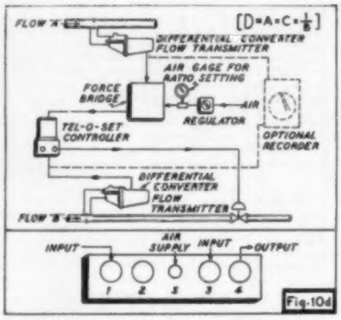

Fig. 10d—Force bridge used to multiply two independent pneumatic signals.

linear output so that the flow receiver can be equipped with an evenly-graduated chart or scale.

Fig. 10b. The squaring function of the force bridge is valuable in applications such as the one shown schematically here, to obtain ratio control of two flows where one flow is measured by a linear flow meter and the other by a square root meter. To provide a suitable signal from the meter on the uncontrolled flow line, the transmitted signal is applied to the Sorteberg unit, which supplies a squared signal to the flow ratio controller.

Fig. 10c. The ratio-setting function is illustrated here. By means of a manually operated pressure regulator, an air signal is used to vary the relationship between input and output pressures. The input signal is multiplied by the signal from the regulator, and the product is the output, which, in this example, resets the index of the controller on Flow "B."

Fig. 10d. The bridge can multiply two independent pneumatic signals as shown in the diagram, schematically.

Fig. 10e. This illustration shows how the bridge can be used to divide pneumatic signals. Two flow signals are transmitted to the unit, which divides one by the other and supplies a signal, representing the quotient, to a recorder. As an example of the use of this arrangement: a record of fuel-air ratio of a combustion process can be ob-

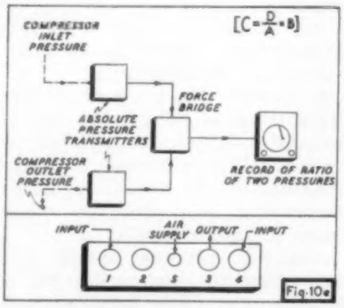

Fig. 10e—Division of pneumatic signals. Two flow signals are transmitted to bridge, which divides one by the other and provides a signal representing the quotient. A record of fuel-air ratio of the combustion process is thus obtained.

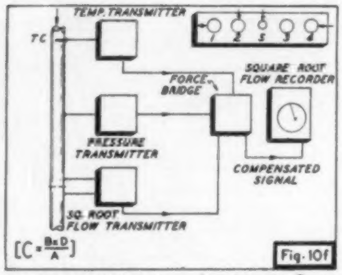

Fig. 10f—Multiplication and division by Servo Force Bridge. Supplies a flow signal with a line *pressure* and *temperature* compensation. Output signal is equivalent to:

$$\frac{\text{Flow signal} \times \text{Absolute pressure signal}}{\text{Absolute temperature signal}}$$

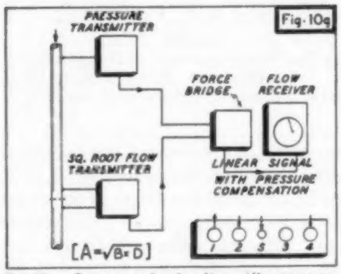

Fig. 10g—Square root extraction with pressure compensation. Signal from the sq. root flow transmitter is at port 2. Output to the evenly graduated flow receiver is from port 1.

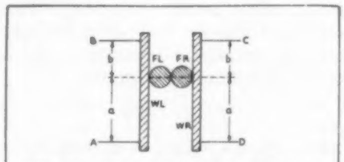

Fig. 10h—Schematic representation of weighbeam system.

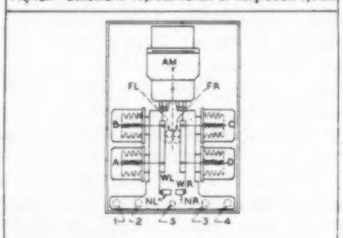

Fig. 10j—Arrangement of load cell and W-B system

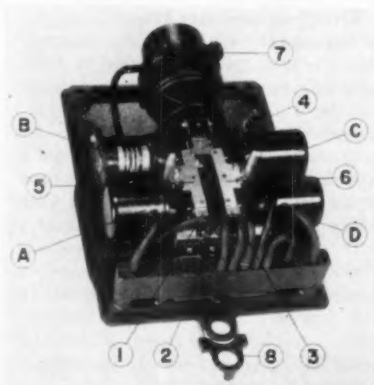

Fig. 10k—Principal components of Sorteberg Pneumatic Servomechanism. Weighbeam system includes fulcrums (located at 4), weighbeams (1) and (3), nozzles (nozzle NL shown at 2), fulcrum rollers and roller guides at (5) and (6), load cells A, B, C and D, lock (8), air motor (7) Cover removed.

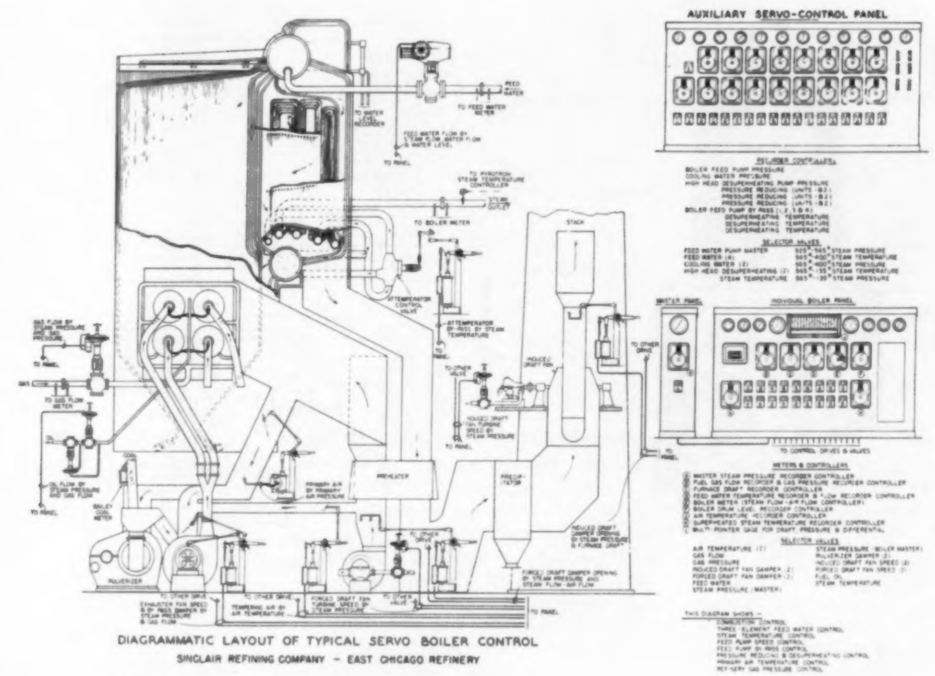

Fig. 11—Electric, pneumatic, and hydraulic servomechanism applications

tained by transmitting air flow and fuel flow signals to the relay.

Fig. 10f and Fig. 10g are explained by the drawing captions.

The basis of operation of the force bridge is a weighbeam system, schematically shown in Fig. 10h and consisting of two parallel weighbeams, *WL* and *WR*, with two fulcrum rollers, *FL* and *FR*. The letters, *A*, *B*, *C*, and *D* represent forces which are perpendicular to the weighbeams. With the system in equilibrium, the moments of these forces around the fulcrums are represented by the following equations:

$$A \times a = B \times b \quad \text{and} \quad D \times a = C \times b \qquad (1)$$

$$A \times C = B \times D \qquad (2)$$

From the second equation above, any one of the forces can be expressed as a function of the other three:

$$D = \frac{A \times C}{B} \quad \text{or} \quad C = \frac{D \times B}{A}$$

$$A = \frac{B \times D}{C} \quad \text{or} \quad D = \frac{A^2}{B} \text{ when } C = A$$

$$A = \sqrt{B \times D} \text{ when } C = A$$

Fulcrum rollers are positioned by an air motor (*AM*) in Fig. 10j to keep the system in equilibrium. As the principle of operation of the force bridge is rather lengthy, we have provided Figs. 10j and 10k as explanatory cuts. Use of the weighbeams in the unit results in the bridge being a true nullbalance instrument, with its accuracy independent of the force required to position the fulcrum rollers, and the use of feedback in the pneumatic balancing of the weighbeam system reduces frictional effects to a minimum.

Another type of air relay which is used in servosystems for amplification, addition, subtraction, and reverse loading pressure is the Standatrol[3] relay. This interesting unit is shown in Fig. 12.

Figs. 13 and 14 illustrate the principle of operation which is of paramount importance in a pneumatic servosystem. This principle is based on the admission or discharge of air from chamber *D* to balance the variations in air loading pressures which may be applied to chambers *A*, *B*, or *C*. An air supply, normally 35 psi, is connected to the inlet valve, and air pressures of 5 to 25 psi are normally used in one or more of the chambers *A*, *B*, and *C*.

A series of springs and bellows exert forces, the amount of spring loading being dependent upon the application of the relay in the loop system. When applied to a servosystem, they are used for averaging, accelerating, differential relaying, totalizing, reversing, doubling, and halving.

In Fig. 14 are shown three typical elements that go to make up a pneumatic servo control system for a feedwater flow circuit. These are: (1) steam flow from the boiler, (2) feedwater flow to the boiler, and (3) water level in the drum. These elements are all automatically controllable. The controlling means in the loop are the force bridge (amplifier), ratio air relay (error detecting), water-level pneumatic transmitter (reference quantity), steam flow pneumatic transmitter (applied control), and the feedwater regulating valve (error correcting device). The selector station acts as "command" or manual reference station.

The steam flow element is sensitive to load demand changes, and immediately detects any changes required as to water flow to the boiler in order to maintain a constant level in the drum. The water level element is affected by "swell" or "shrinkage" and lags somewhat in detecting the true water flow requirements at the time of a load change. Consequently, the steam flow element gives the primary signal or initial adjustment of the system. The water flow element signal opposes that of the steam flow element in order to maintain a desired ratio of water flow to steam flow. This assures that the rate of flow of feedwater to the boiler is proportional to steam flow. The water-level element readjusts the control system to maintain desired level by compensating for system characteristics which may occur at any given boiler load, such as variations in rate of blowdown, variable differential pressures across the feedwater regulating valve, etc.

Control of a Two-Phase, 65-Watt Servomotor

Before discussing this combustion application in general, the tachometer and servo-control motor involved will

[3] Bailey Meter Co.

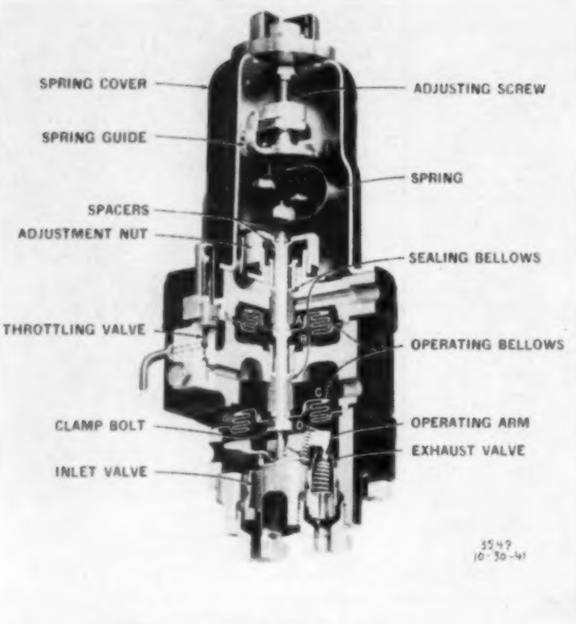

Fig. 12 – Air-type servo relay assembly.

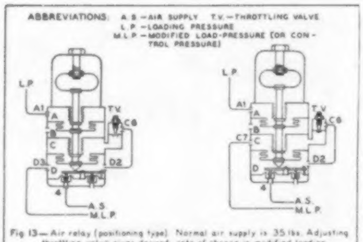

Fig 13—Air relay (positioning type). Normal air supply is 35 lbs. Adjusting throttling valve gives desired rate of change in modified loading.

Fig 14—Air relay (floating type). These units amplify, add, subtract, and reverse loading pressures which are received from servo loop sources.

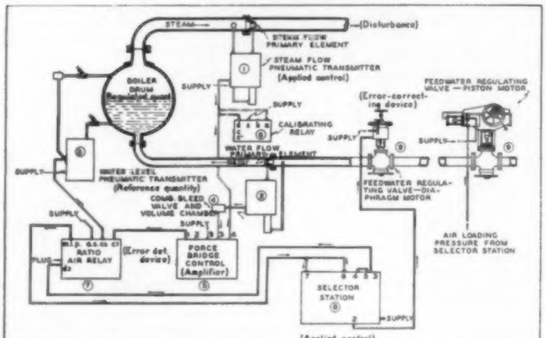

Fig. 15—Pneumatic servosystem "loop" as applied to the control of boiler feedwater flow.

be examined. Fig. 16 shows a linear d-c tachometer used as the feedback device. This unit provides a d-c signal very closely proportional to speed. It is designed for continuous duty over an ambient temperature range of −55 deg C to +55 deg C at speeds up to 4000 rpm. As a voltage source, it is generally connected to high resistance loads—often to vacuum tube elements. The commutator is built of coin silver.

Fig. 17 shows the servo-control motor involved in the application. This unit is designed with a rotor of very low moment of inertia for rapid acceleration and deceleration, such as is encountered in servomechanisms. In addition, their sloping speed-torque characteristics permit wide application to systems requiring adjustable or variable speed. This motor is center-tapped at the high-impedance control winding for direct connection to a push-pull amplifier output, thus eliminating the weight, space and wiring ordinarily necessary with the usual coupling transformer. The moment of inertia is 0.58 oz.-in.^{2}

This servomechanism[4] was designed with a maximum output of 65 watts which was needed for a combustion application. It should have the minimum possible weight and the lowest power consumption consistent with reliability, long life, and a 10-cycle frequency response.

The 2-phase servomotor drive seemed best for this application (automatic control of coal feed, motor-rheostat from exhauster). Hydraulic servomotors are too heavy for this low power output, and there was no hydraulic system available—the combustion control being pneumatic and electric.

The motor used was a Diehl type SS-ZP105-2217-1 servo-blower motor, modified to fit this job. The apparent 200-watt rating of the motor was also modified down for 65 watts of motive power with only a 30 per cent loss in efficiency. Rated at 115-v, at 2 amp per phase, the power input at stall condition is 115 watts per phase, and the maximum speed is 4000 rpm. Motor and its blower weigh 6 lb.

Possible Method of Motor Control

Thyratrons. Four methods of controlling the power into the control phase of the motor were considered. Thyratrons were ruled out largely because ripple in the control signal could cause erratic operation and partly because of the large heater power required at standby.

Vacuum Tube Amplifier. The vacuum tube circuit of Fig. 18 required relatively many, heavy transformers, a relatively large volume to house the tubes, and a heater power of 60 watts. The overall efficiency was 50 per cent.

Simple Reactor Bridge. The simple reactor bridge-type magnetic amplifier circuit of Fig. 19 was built and tested and found to give satisfactory motor control. When a d-c signal is placed on the tube grids to cause tube

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[4] Consumers Power Company, Jackson, Michigan.

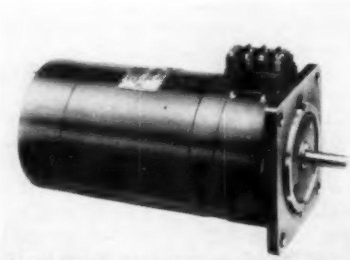
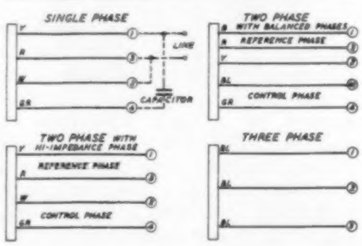


Fig. 16—Linear d.c. tachometer used for servomechanism "feedback" function.

D.C SERVO-TACHOMETER CHARACTERISTICS CHART			
LINEARITY	LESS THAN .02%	INERTIA	3.7 oz.-in.^{2}
RIPPLE	LESS THAN .04%	MAX. SPEED	4000 RPM
OUTPUT VOLTAGE	0.75 ± [illegible]v/1000 RPM	FRICTION TORQUE	0.5 oz.-in.
ARM. RESISTANCE	80.0 ± 8 OHMS	WEIGHT	6 LBS

Fig. 17—Low-inertia servocontrol motor for instrumentation and temperature supervision.



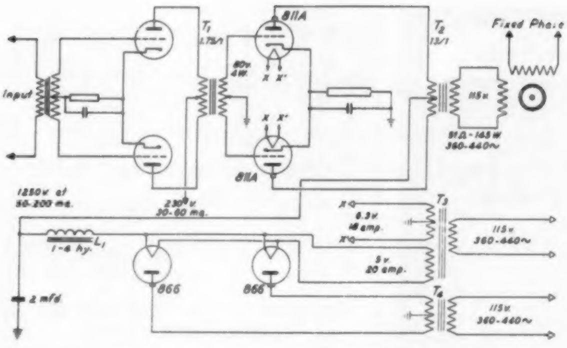


Fig. 18—An electronic circuit for the control of the 65-watt, 2-phase servomotor unit

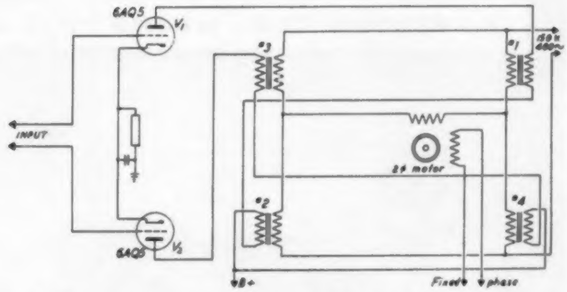


Fig. 19—Bridge circuit using saturable reactors for control of the 2-phase servomotor.

V_1 to conduct, reactors *1* and *2* become saturated by the flow of plate current so that the motor control winding is effectively connected across the a-c supply. Reversing the polarity of the signal applied to the grids causes reactors *3* and *4* to become saturated while reactors *1* and *2* become a high impedance so that the control winding is connected across the a-c supply in the opposite polarity, reversing the motor.

This simple circuit has a number of disadvantages. As in all simple reactor amplifiers, the average a-c ampere-turns on the reactor must equal the average d-c control ampere-turns. In the design that was tested 60 milliamperes were required in 22,000 turns to obtain the desired 2-amp motor current. The 6AQ5 tubes which were used required a + or -25 v d-c signal on the grids. In this particular servo a d-c amplifier having the required voltage gain could not be fabricated with a convenient tube lineup. Considerable plate and filament power is required and the time delay is somewhat longer than for a self-saturating circuit. The toroidal reactors are difficult to construct because of the large number of control turns required.

Self-Saturating Bridge. The circuit finally chosen is the much-used[5] self-saturating circuit of Fig. 20. The total weight of the reactor unit, autotransformer, and rectifiers is 5.5 lbs. Because of the larger power gain of the self-saturating circuit, a control current of 6 milliamperes in 1200 turns is all that is required for full output. The *5744* subminiature control tubes required only plus-minus one volt on the grid. This circuit, in common with the simple reactor circuit, was unaffected by large amounts of ripple on the signal applied to the tube grid.

One parallel self-saturating magnetic amplifier, sometimes called a "doubler," is used for each direction of rotation. When amplifier 1 of Fig. 20 is saturated, the motor is effectively connected across one-half of the transformer. Amplifier 2 then has high impedance and has a total voltage of one-half of the transformer plus the voltage across the motor. Reversing the polarity of the signal applied to the tube grids reverses the previously discussed situation so that the current in the motor control winding changes phase 180 deg to cause motor to revolve in opposite direction.

The linearity of the motor torque versus signal curve is improved if the bias is adjusted so that a circulating current of about 0.4 amp flows through the two amplifiers when the motor current is zero. This type of amplifier will give full output unless bias ampere-turns are applied to reduce the output. If the bias fails, both amplifiers have a low impedance, thus effectively short-circuiting the transformer. The current which flows can be many times the maximum motor current and may burn out the rectifiers or reactors.

Design of the Amplifier

On the basis of previous experience, it was estimated that the transformer voltage applied to each amplifier should be about 50 per cent greater than the voltage which was desired on the motor. This extra voltage is lost in resistance drop across the reactors and rectifiers, and permits the amplifiers to be operated in the linear area of the transfer characteristic—that is, up to about 80 per cent of their maximum output. The transformer voltage was therefore made 175 volts on each side of the center tap.

The reactors then should be designed for a transformer voltage of 175 plus the maximum motor voltage of 115 volts, or 290 volts. On a 400-cycle a-c system having + or -5 per cent voltage and frequency regulation, the reactors would be designed for 305 v at 380 cycles.

If a magnetic amplifier is used for power control, as in this instance, the reactor may be described completely by specifying the voltage at which the power winding of the reactor saturates and the resistance of the power winding. The best reactor design is that which has the lowest weight for a given power winding resistance. This assumes that a large control power is available so that the power gain need not be maximized.

A large number of reactors were designed using cores made from 0.5-in. Hypernik V strip with various outside and inside diameters. From the results of these designs as plotted in Fig. 21, the design which gives the minimum reactor weight for a given power winding resistance can be selected. On the basis of about 14-v maximum resistive voltage drop, a power winding resistance of 7 ohms is desired. In position servomechanism service the reactor must be designed for large peak outputs. It was estimated that with a 7-ohm power winding resistance the low average power output would not heat the reactors to their 50-deg C allowable rise. For this particular power winding resistance a core having an inside diam of 1.5-in. and a 0.5-in.-sq cross section is convenient because of its weight.

Since a magnetic amplifier shifts the phase of the voltage applied to the control field as well as changing its amplitude, it was thought that the motor torque might be a non-linear function of the control voltage. Fig. 22 shows

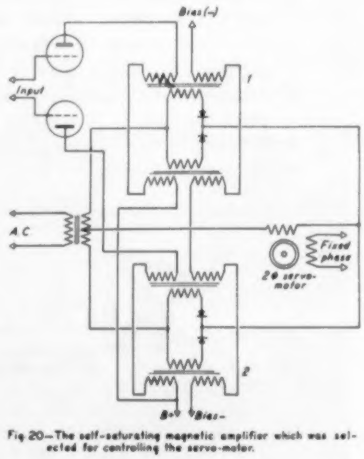


Fig. 20—The self-saturating magnetic amplifier which was selected for controlling the servo-motor.

[5] "Magnetic Amplifiers," S. E. Tweedy, *Electronic Engineering* (London, England), Vol. 20, March 1948, pages 84–8.

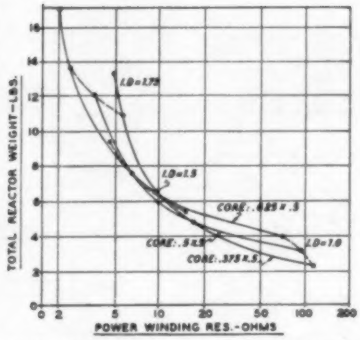


Fig. 21—Reactor design curves. Total reactor weight includes weight of copper and iron.

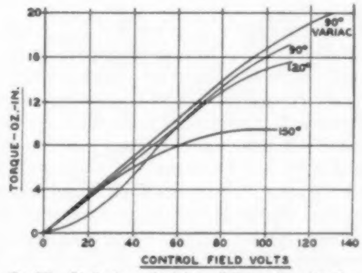


Fig. 22—Stall characteristics of the motor with the magnetic amplifier supplying power to the control field for various values of phase shift of the fixed field of the 2-phase servomotor.

the magnitude of this effect. The curves were obtained by use of a variac. The torque obtained with magnetic amplifier control is always somewhat less than that obtained with a variac because of distorted waveshape.

In over a year of servo testing there have been no failures of either the reactors or the rectifiers. The motor-control amplifier is now considered to be a successful development and plans for three others are now being considered for coal-feed control.

Abstracts From the Technical Press—Abroad and Domestic

(Drawn from the Monthly Technical Bulletin, International Combustion, Ltd., London, W.C. 1)

FUELS: SOURCES, PROPERTIES AND PREPARATION

The Grinding of Coal in a Ring-Ball Mill. Joint Committee Fuel Research Board and British Coal Utilisation Research Assn. *J. Inst. Fuel 1957*, **30** (*May*) *269–76.*

Following the tests described in the Interim Report (*J. Inst. Fuel 1955*, **28** (*Jan.*) *30* further tests were carried out over an increased range of operation. The relationship between mill power and mill output passing 200 mesh sieve times coal rate was shown to be dependent on plant setting and a broad scatter of experimental points was obtained with each coal. The lower boundary of this scatter is almost linear and represents a line of maximum efficiency in each case. The slopes of these boundaries can be taken as criteria of performance and show a relation with the Hardgrove Index. Information is also given on: 1. Distribution of air pressure and temperature in the mill; 2. Movement of grinding elements; 3. Influence of air leaving the mill on moisture content of pulverised coal; 4. Effect of pressure of grinding elements on performance coefficient and maximum output of the mill.

Ball Mills and Ball Milling. Part II. T. G. Callcott. *BCURA Monthly Bull. 1957*, **21** (*April*) *153–71.*

The review is continued with: 5. some theories of ball milling; 6. pulverising coal.

The Practical Application of Coal Sample Theory. G. Woodhouse. *J. Inst. Fuel 1957*, **30** (*May*) *249–62.*

The variance of ash content of samples in which different constituents of a coal are included in a random manner is considered based on fundamental principles of theoretical statistics. It is shown that sampling depends mainly on the grading of coal and that average ash content and the manner of distribution of the ash between the various sizes plays only a secondary part. The variance of grading is also considered and a new formula proposed. Simple approximations to the estimation of theoretical variances are put forward which may prove useful in practice. Experimental determinations of sampling and reduction variances should be compared with optimum values estimated theoretically to make use of the extensive work on coal sampling theory already available.

A Method for the Measurement of Heat Generation in Powdered Coal. P. C. Newman. *Brit. J. Appl. Phys. 1957*, **8** (*Apr.*) *162–7.*

A new method is proposed for measuring the generation of heat in coal or other finely divided powders. This method depends only on the thermal constants of the material and not on the heat losses to the surroundings of the calorimeter. New solutions to the heat flow equation for heat generation in cylindrical and spherical bodies as required for calculating the results are presented, and experimental confirmation of the suitability of the method is obtained. During the course of the work an interesting result is obtained on the critical sizes

of systems which generate heat at a rate which increases linearly with temperature.

MECHANICAL HANDLING

Coal Handling Plant Modernization. J. M. Beskine. *Mech. Handling 1957*, **44** (*May*) *264–71*.

A plant for unloading wagons, transporting and distributing the coal to the storage bunkers and unloading from these into lorries is described. The working of the whole plant is supervised from a single central cabin containing all controls. The result of the new installation has been a very considerably speeding up of all operations thus enabling a larger tonnage to be handled than previously.

Hydraulic Transport of Slurries Through Pipelines. F. Pickert. *Fördern u. Heben 1957*, **7** (*May*), *200–4*. (*In German.*)

Various possibilities of pneumatic transport of slurries are described, especially twin-tank installations which allow continuous operation. The dependence of the efficiency of such systems on the pressure applied is discussed together with means of reducing flow resistance and simultaneously maintaining a stable slurry. It is shown that by correct mixing of various sizes of the solid and a correct solids to water ratio a minimum of pressure is required and an optimum efficiency can be obtained for given conditions. This would apply specially to the transport of coal and similar materials. Several examples of recent installations are illustrated.

Linear Induction Pumps for Liquid Metals. A. S. Fenemore. *Engineer 1957*, **203** (*May* 17), *752–5*.

STEAM GENERATION AND POWER PRODUCTION

General

Pressure Vessel Design. Anon. *Brit. Weld. J. 1957*, **4** (*May*), *223–9*.

The report of Commission XI, Sub-Commission B: Allowable Stresses, of the Intern. Inst. of Welding is presented. This deals with: 1. Broad bases for determining design stress; 2. the design process; 3. detailed evaluation of design stress; 4. low-carbon steels at 20 and 350°C; 5. low-alloy steels at 20 and 410°C; 6. maximum permissible stresses in other parts of a pressure vessel; 7. values of K for various parts of a pressure vessel; 8. permissible out-of-roundness; 9. Appendices.

Acid Cleaning of Steam Generators. L. Astrand. *Mitt. V.G.B. No. 47, 1957*, (*Apr.*) *101–7*. (*In German.*)

Recent Swedish practice of cleaning new and old boilers is described with special reference to inhibitors, corrosion during and after cleaning and the procedures to be followed.

The Problem of Combined Insulation, Especially Pipe Insulation with Mineral Fibre Woods and Blankets. H. Seiffert and H. Wagner. *Energie 1957*, **9** (*Apr.*) *130–6*. (*In German.*)

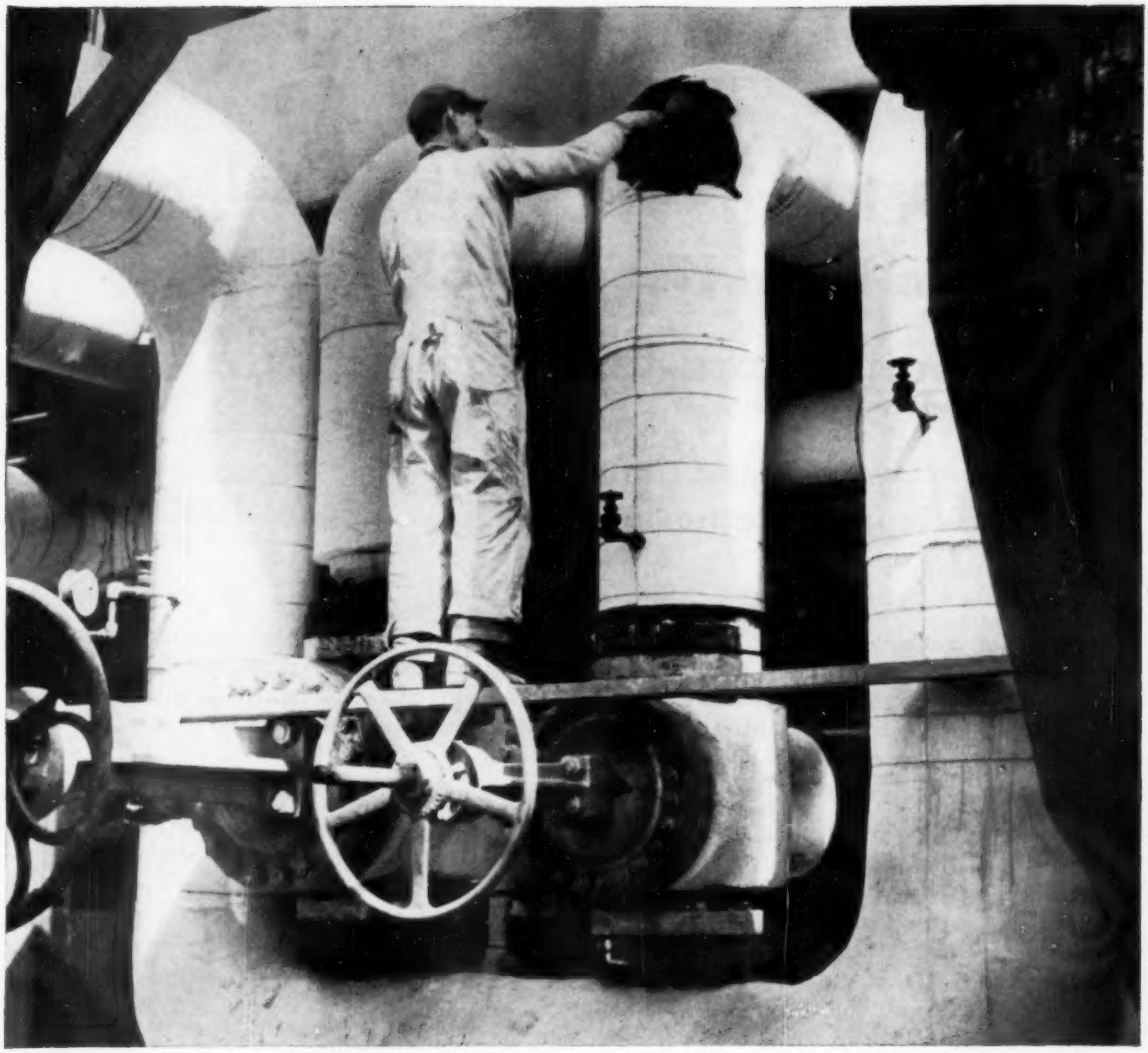
Equations have been developed for deciding whether the use of one or more insulating materials results in the lowest heat loss under given conditions and total insulation thickness. The application of these equations is illustrated by several examples.

You Can Control Piping Vibration. V. V. Cerami. *Power 1957*, **101** (*May*), *115–7*.

The sources of vibration of pipe lines are discussed and methods of preventing or reducing vibrations described.

The Starting of Hydrogen Decarbonising Plants. J. Schmidt. *Mitt. V.G.B. No. 47, 1957*, (*Apr.*) *117–22*. (*In German.*)

The main points to be considered when starting and regenerating a hydrogen ion exchanger plant are discussed.



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GAS CLEANING NEWS

Eastern Public Utility Installs Two More Koppers Electrostatic Precipitators to Remove Fly Ash

Major Utility has installed 8 Koppers Electrostatic Precipitators since 1947

YEARS of cost-saving, highly efficient performance preceded this latest installation of Koppers Electrostatic Precipitators. During these years, this leading Eastern public utility was able to judge Koppers by on-the-job operation—the most positive proof of performance.

Proves Performance on the Job

Ten years ago, this company purchased its first two Koppers Electrostatic Precipitators for fly ash removal. Satisfactory performance and low maintenance costs justified the purchase of additional Koppers units that were installed in a total of 4 stations. The eight units furnish highly effective, trouble-free operation in a varying range of CFM capacities.

Supplies a Wide Range

The eight Koppers Electrostatic Precipitators serve boilers ranging in capacity from 570,000 #/hr to 950,000 #/hr. Guaranteed efficiency runs as high as 98%, depending on the need of each application. This ability to engineer for a wide range of capacities enables Koppers to satisfy the needs of each station.

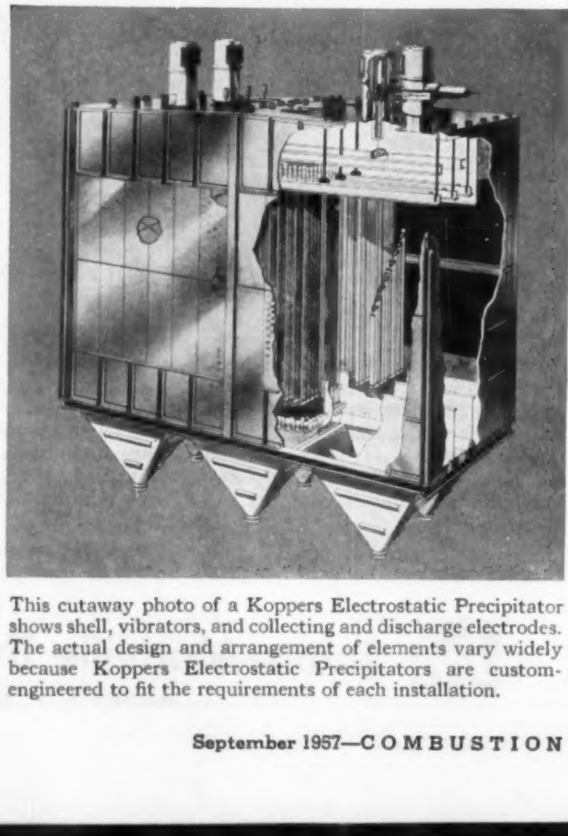
Meets Individual Plant Needs

Koppers custom-designs each Electrostatic Precipitator. Koppers units remove boiler fly ash before the flue gas is discharged from the stack. In designing Electrostatic Precipitators, Koppers utilizes its knowledge of the characteristics of various coals, types of boilers and methods of firing.

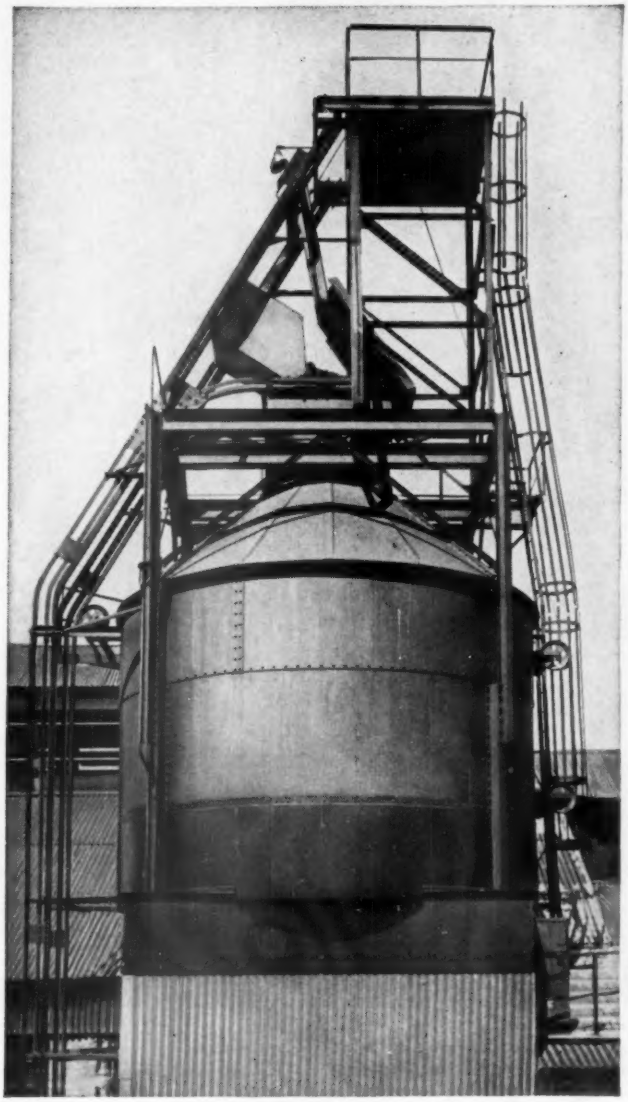
Backed by Know-How

Koppers gas cleaning experience goes back 75 years. This experience is backed up by extensive research facilities at Verona, Pa., and Baltimore, Md. From this experience and research has come gas cleaning equipment for all sizes and types of plants.

Get the most out of your gas cleaning dollar. Write KOPPERS COMPANY, INC., Metal Products Division, Industrial Gas Cleaning Dept., 4409 Scott Street, Baltimore 3, Maryland.



This cutaway photo of a Koppers Electrostatic Precipitator shows shell, vibrators, and collecting and discharge electrodes. The actual design and arrangement of elements vary widely because Koppers Electrostatic Precipitators are custom-engineered to fit the requirements of each installation.



LOW COST DEPENDABLE COAL HANDLING FOR PUBLIC UTILITIES

Salem Gas and Light Company, Salem, Mass., found a G-W Skip Hoist the ideal solution to the problem of conveying coal and coke to producer storage. The skip bucket keeps the producer-storage bin filled at all times . . . and does the job with maximum economy.

Gifford-Wood Skip Hoists . . . one of many G-W systems of materials handling . . . are low in initial cost . . . low in maintenance . . . long-lived . . . completely dependable. Public utility companies the country over are becoming increasingly interested in Skip Hoist handling of coke, coal and ashes where space is limited and both initial and operating costs must be kept at rock bottom.

This particular installation may not be the perfect solution to your own particular problem. Gifford-Wood, however, has specialized in the design, engineering and installation of all types of materials handling systems for 136 years. To have a Gifford-Wood Materials Handling Engineer survey your present method of moving materials, places you under no obligation and it may well be your first step toward lower operating costs and increased production.

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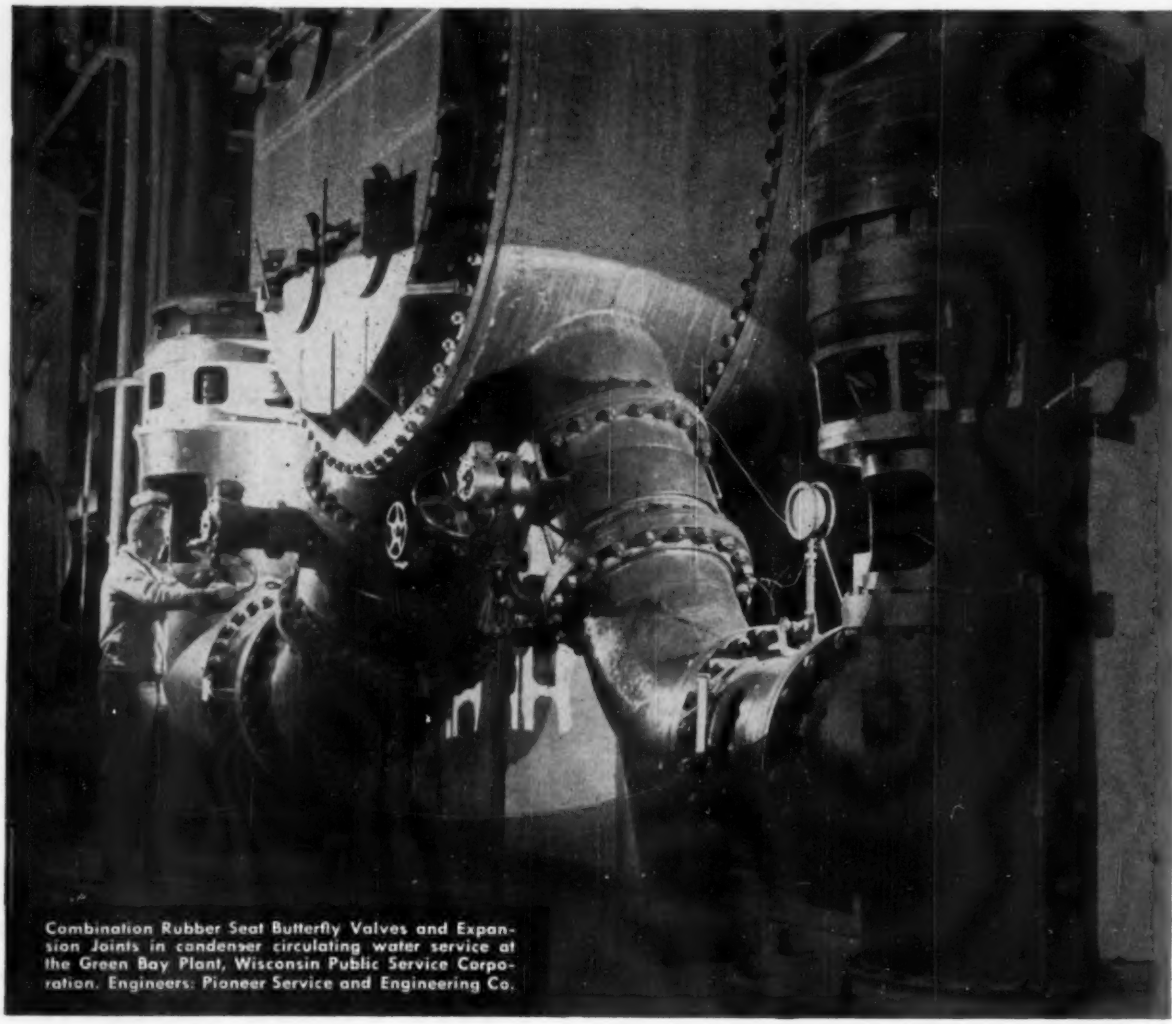

Combination Rubber Seat Butterfly Valves and Expansion Joints in condenser circulating water service at the Green Bay Plant, Wisconsin Public Service Corporation. Engineers: Pioneer Service and Engineering Co.

GREEN BAY...Combines Butterfly Valves with expansion joints for new economy

Drop-tight shutoff, plus provision for pipeline expansion and ease of assembly are provided here in one compact Pratt unit. By combining the Butterfly Valve with the expansion joint, space requirements are minimized and maintenance (and initial cost) of one set of flanges and bolts is eliminated. This is a typical Henry Pratt engineering job—the mechanisms are the simplest available . . . for economy and minimum maintenance, and they are carefully designed and built for peak efficiency and operating ease.

Henry Pratt pioneered the use of Rubber Seat Butterfly Valves in power plants. Combined with permanently drop-tight shutoff, the inherent simplicity and compactness of this valve permitted a new concept of large-diameter valving by power plant engineers.

Pratt Rubber Seat Butterfly Valves grew with the Power Industry for thirty years, and today are being installed in modern, nuclear power plants. For valve design—with **imagination**—see Henry Pratt.

NEW! Latest, most accurate pressure drop and flow data, conversion tables, discussion of butterfly valve theory and application plus other technical information . . . Write for ManualB-2D.

HENRY PRATT

RUBBER SEAT **Butterfly Valves**

Henry Pratt Company, 2222 S. Halsted St., Chicago 8, Ill. Representatives in principal cities

Unretouched photo of dissolved oxygen attack in steam condensate return lines.

DEPOSIT OF NO RETURN

The "growths" you see on the interior of this condensate return line are known as tubercles. Beneath each tubercle is a cavity or pit in the metal surface—the result of concentrated, localized attack by the corrosive water. Water containing dissolved oxygen has converted metal on the pipe's interior to iron oxide, causing a buildup of corroded material. The velocity of the water flowing through the line is not sufficient to remove the tubercles, so they continue to grow larger and larger.

Dearborn's FILMEEN* prevents this corrosive attack by forming a continuous, monomolecular film on the interior surface of the pipe, protecting it against both oxygen and carbon dioxide corrosion. FILMEEN provides a protective, non-wettable barrier between treated steam, or condensate, and metal pipe surfaces.

FILMEEN is only one of many Dearborn water conditioning products scientifically developed to control specific corrosion problems. Others eliminate scale, sludge, carryover, and similar difficulties.

Power engineers in leading industrial and commercial plants place their confidence in Dearborn's 70 years of experience in water chemistry. They have found the answer to the demand for complete plant protection in Dearborn Supervisory Service—a properly balanced water conditioning program which combines quality products with correct, technically supervised control methods and test procedures.

Let a Dearborn Engineer survey your plant and recommend the type of water control program best suited to your requirements.

Illustrated Booklet gives all the facts on Dearborn Water Conditioning Program. The coupon is for your convenience.

**FILMEEN is the trade-mark of a corrosion-inhibiting compound patented and produced exclusively by Dearborn Chemical Company. U. S. Pat. No. RE 23614.*

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Apexior Number 1 for boilers ®

HOW MUCH CLEANING IS NECESSARY BEFORE APEXIOR-COATING?

A surface no cleaner than good operating practice demands is all the foundation needed for Apexior Number 1 — the coating that ever after holds steel at newly cleaned efficiency.

HOW DOES THE DAMPNEY TEST KIT SERVE?

By saving man-hours that might be expended needlessly. A quick, three-step check tells when cleaning has delivered just-right surfaces, prepared neither less nor more than necessary.

DOES THE APEXIOR-COATED BOILER STAY CLEAN IN SERVICE?

Because Apexior discourages deposit formation and bonding, the coated boiler needs less cleaning, less often. Inspection is easier, too — for a sound Apexior surface reveals itself readily, assuring equally sound steel 2½ mils beneath.

DOES CHEMICAL CLEANING AFFECT APEXIOR?

In no way. Rather, Apexior takes on the added function of preventing acid-metal contact and the resultant attack, however slight, that might occur. Those engaged in chemical cleaning report that Apexior speeds the process by keeping deposits few and less tenacious.

WHEN SHOULD A BOILER BE APEXIOR-COATED?

To seal water-contact surfaces permanently at highest efficiency and take them safely through the initial shake-down period, a new boiler should be Apexior-coated immediately after erection; an operated boiler, immediately after cleaning.

IS APEXIOR BOILER COATING DIFFICULT?

Not at all. Apexior is brush applied — by hand to drums and flat areas; by air-driven tube turbine, brush-equipped, to tube interiors. Application is regularly made by plant crews with or without initial Dampney supervision.

HOW LONG DOES APEXIOR LAST?

A conservative estimate: Five years before retouching or renewal. Under ideal conditions: Ten to twelve . . . for Apexior's primary function is preventive maintenance — its life, directly proportional to the work it has to do in supplementing good boiler practice.

This message — one of a series — presents more reasons why Apexior Number 1, first used inside boilers in 1906, is today manufactured in the United States and four foreign countries to meet world-wide demand for protection of

- *boiler tubes and drums*
- *evaporators*
- *deaerating and feedwater heaters*
- *steam turbines*

MAINTENANCE FOR METAL

THE DAMPNEY COMPANY

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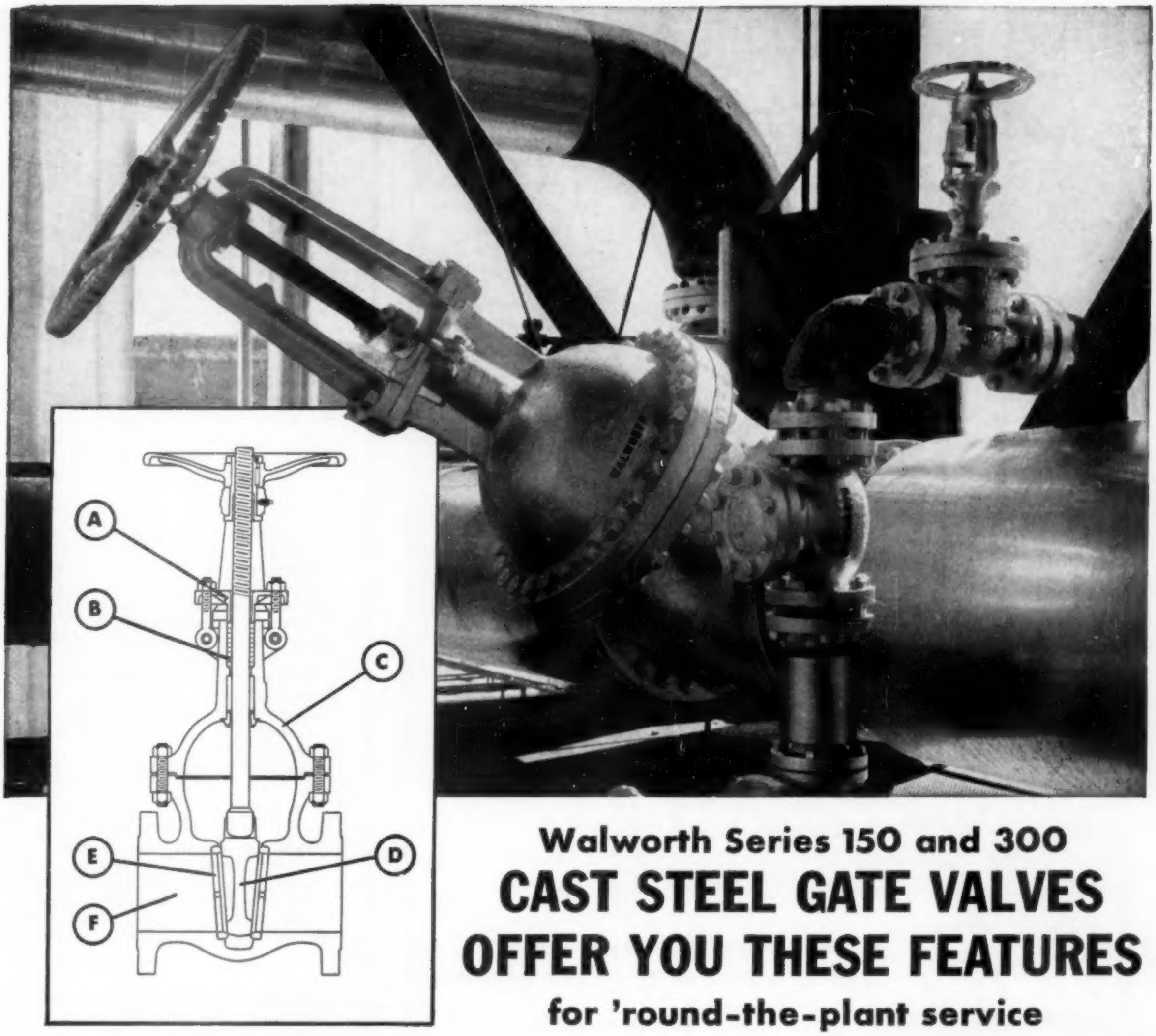

Walworth Series 150 and 300

CAST STEEL GATE VALVES OFFER YOU THESE FEATURES

for 'round-the-plant service

(A) GLANDS: Clearances between the gland and stuffing box, and gland and stem, are such that the stem cannot be scored even if the gland is pulled down unevenly.

(B) DEEP STUFFING BOXES: More than adequate in all sizes (2" to 24") to assure tightness and maximum packing life.

(C) BONNETS AND BODIES: Engineered to exceed the requirements of all applicable codes and standards. They are tough, durable, dependable.

(D) INTEGRAL GUIDE RIB FACES IN BODY: Machined to insure accurate centering of the gate.

(E) STURDY SEAT RINGS: Bottom-seated so that no recess exists at the back of the ring to cause turbulence, erosion and pressure drop.

(F) STREAMLINED PORTS: Permit unobstructed flow which results in minimum pressure drop and reduces the possibility of erosion.

Walworth Cast Steel Gate Valves can be furnished with either flanged ends or butt welding ends. Roller bearing yokes are available on the larger sizes. On valves 4 inches and larger, by-passes can be furnished. Walworth Cast Steel Gate, Globe and Check Valves from Series 150 to 2500, are available. For Series 600 and higher, we recommend Walworth Pressure Seal Cast Steel Valves. See your Walworth Distributor or write to Walworth for complete information.

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Advertisers' Index

(Continued on page 71)

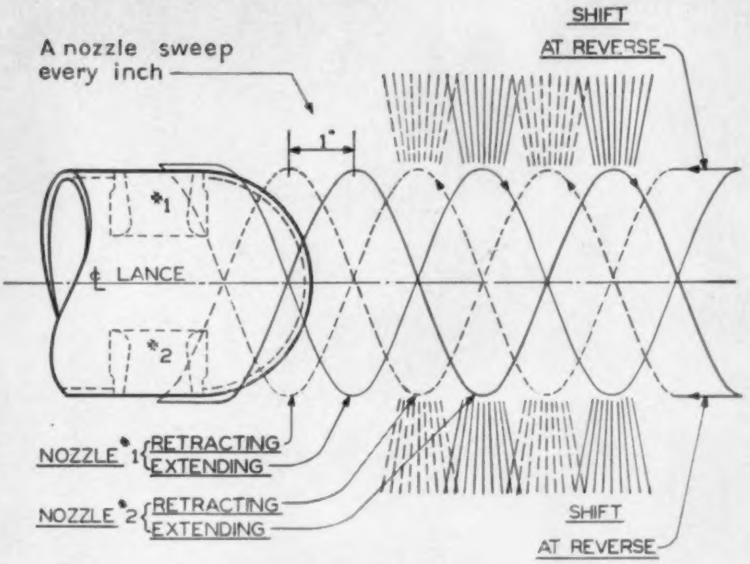
IMPROVED CLEANING PATTERN

another important feature of the

New Diamond Series 300 IK LONG RETRACTING BLOWER

The positively-controlled, close helical cleaning pattern assures optimum coverage of the heating surface. Return travel path is exactly intermediate to forward travel path . . . resulting in a positive nozzle sweep every inch.

This is another of many reasons why the Diamond Series 300 IK Blower does a better and more economical job of cleaning surfaces which require a long retracting blower. Other advantages are listed at the bottom of the page. Ask the nearest Diamond office or write directly to Lancaster for Bulletin2111V which will tell you much more about the new Series 300 IK.



Nozzle-sweep-every-inch blowing pattern assures COMPLETE coverage of ALL surface EVERY time

OTHER ADVANTAGES OF SERIES 300 IK BLOWERS

- Backbone and Protective Cover
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- Compact, Accessible Electric Power and Control Terminal Facilities
- Improved Blower Nozzle
- Positive Gear Carriage Drive
- Poppet Valve with Adjustable Pressure Control
- Positive Mechanically Operated Valve
- Single Point Outboard Suspension
- Oversize Lance (Step-Tapered for Extra Long Travel)
- Auxiliary Carriages for Extra Long Travel
- Designed for Quick, Easy Servicing

No other blower gives you all these advantages.

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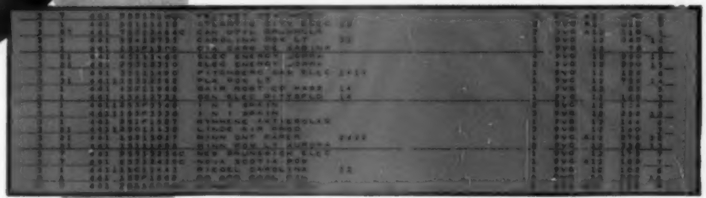
For Fly Ash Collection, here are
3,370 REASONS WHY

You're Years Ahead with MULTICLONE



The tabulation sheet shown here is over 40 feet long, filled top to bottom with single-spaced typewriter listings as shown in the enlarged section above...

- Each typewritten line tabulates an installation of Multiclone equipment—an installation of from one to nine separate Multiclone units!
- These installations have been made in all parts of the world, in plants operating under widely-varying load, atmospheric and fuel conditions!
- They include installations on virtually every type of steam power plant (i.e. pulverized coal fuel boilers, spreader stoker boilers, chain grate boilers, underfeed stoker boilers, etc.)

New Multiclone installations are being made every day, but at the time this tabulation was made there were 3,370 Multiclone units giving superior service to industry throughout the United States, Canada and other countries.

What does this mean to you? Simply this—when you select "Multiclone" you are getting equipment that has over a quarter-century of experience behind it...equipment backed by the industry's greatest fund of "know-how" in modern small tube, high-efficiency cyclonic collection. Although this unequalled experience is a part of every Multiclone installation, you pay nothing extra for this vital advantage!

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MULTICLONE Mechanical Collectors
CMP Combination Units
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